Shape exploration in product design: assisting transformation in pictorial representations

Thesis

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The Open University

Shape Exploration in Product Design

Assisting Transformation in Pictorial Representations

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Abstract

The sketching of pictorial representations forms a key technique for professional designers in the generation and exploration of product shape. It allows ideas of shape to be externalised and communicated, but more importantly, sketched pictorial representations can operate to assist designers' creative thinking. While computer aided design tools have a proven capability to support the development of design ideas, there is still much scope to develop computer based tools that support the free-flowing exploratory thinking that characterises shape generation and shape exploration in product design. Far from being a straight-jacket in creative design, shape rules have significant potential to bridge the gap between traditional sketching techniques and modern computational methods of design. This thesis presents an inquiry into the exploitation of shape rules within product design. It includes studies of design sketches by professional designers and these inform the development of a theoretical model for assisting design transformation. A formal model of exploration is proposed with two mechanisms; shape decomposition and shape transformation. This model is applied using pictorial representations which may be seen as the computing equivalent of freehand sketches, and reveals new strategies for systematic shape generation and exploration in product design.

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Chapter 1

Introduction

Design as an activity is, to some extent, something we all undertake in our lives. We decide our own style, we arrange the furniture of our rooms, and we plan our daily schedules among many other tasks that require processes similar to design. However, design activities are more visible in creative professions such as art, architecture, engineering, graphic design, and product design. Whilst there may be some dispute about the precise definition of the term 'design', it is recognized as a purposeful and creative activity. Design seeks to create things with the purpose of satisfying certain requirements in new ways. In product design, a variety of requirements must be considered ranging from functionality and usability to pleasure. However, design is more than just translating a set of requirements into a product. Also, and more importantly, it involves finding new requirements. Thus, design involves finding problems and solutions simultaneously, and this is where creativity is important.

In recent years a number of studies have taken place with the aim of identifying and understanding aspects of creativity in design (Candy and Edmonds 1996; Christiaans and Dorst 1992; Goldschmidt and Tatsa 2005). These studies suggest that creative designing involves movement from one 'solution space' to another. According to Cross (1997), this is what characterises creative design as exploration, rather than search.

Design exploration can be performed in many different ways. Some designers, especially those interested in the visual composition of objects, explore designs according to guiding principles of composition (Stiny 2006). Recent studies have shown that personal cognitive processes, such as perception and thinking, contribute to the designers' ability to explore designs (Oxman 2002). Smithers (2001), suggests that design exploration should be understood as a personal activity; situated in the context and conditions of the designer and design requirements.

Design exploration offers an intriguing opportunity for new types of computer support (Woodbury and Burrow 2006). Exploration is rarely supported by current design tools, partly because there is a lack of understanding of the cognitive processes used to explore designs. Some design tools and the associated generative systems provide models for generating designs that satisfy a fixed set of requirements. Although these tools might be useful in specific situations, they are less helpful in supporting design exploration. Exploratory design tools should allow designers to adapt and change requirements and the solution space as the design process evolves (Maher et al. 1996). This thesis presents a new model that addresses processes necessary to design exploration. It aims to assist and enhance designers' abilities to explore designs through computer tools.

1.1 Processes of design generation and exploration

Understanding the processes of design generation and exploration is not straightforward. Most of these processes are inaccessible because they take place in the designer's head. Comprehending how designers think and how they undertake their tasks is a problem that has intrigued many researchers. One plausible way of uncovering aspects of a designer's thinking process is through examination of their pictorial representations, because there is accumulated evidence that pictorial representations might be considered extensions of thought processes (Scaife and Rogers 1996; Schön and Wiggins 1992; Tversky 1999). The most used type of pictorial representations among designers has traditionally been freehand sketches. Sketching can operate to assist designers in the development of different qualities of products such as form and shape. Sketches are easy to use, flexible, and often ambiguous which seem to support the designers' thinking process (Prats and Garner 2006). Thus, sketches do not only serve to make internal thoughts visible but it is assumed that there is a reciprocal relationship between designers' thinking and their sketches (Schön 1983). In other words, sketches may be a consequence of thinking but also thinking may be stimulated by perception of sketches.

Different strategies are used to generate design alternatives but there is much support for what Darke (1979) characterised as a solution-focused process, that is, the use of conjecture to stimulate analysis and progression in design. Sketches would appear to offer very relevant support to this style of thinking because they can capture and externalise partly formed thoughts and ideas (Garner 1994). Given the existence of such conjecture Guilford (1967) suggests that there are two ways forward. A designer can generate a new idea or explore variations of the existing idea. Researchers of design have argued that the design process is in general convergent (Cross 1994), and this lends weight to the notion that design is largely a process of exploration rather than generation. However, it is the interaction of exploratory and generative processes that is important in design thinking. Although there may not always be a clear distinction between these two concepts, generation tends to be concerned with formulating and refining a concept design, while exploration is concerned with analysing and interpreting a concept in order to suggest new directions for generation.

Consider for example the freehand sketches produced by Philippe Starck to design the well-known *Juicy Salif* lemon squeezer. Figure 1.1 shows the final design, on the left, and a sequence of sketches produced during the design process, on the right. The sequence of sketches seems to follow an anti-clockwise path, starting from ideas that resemble existing lemon squeezers, to the final design. Lloyd and Snelders (2003) point out that these design alternatives are driven by personal intentions and experiences of the designer. What this example attempts to show is that, even if the solution space of all possible lemon squeezers is immense, it seems that the designer quickly focused onto one particular concept – composed of a central body supported by three legs. Woodbury and Burrow (2006) suggest that designers consider a very small number of alternatives in their works in comparison with all possible solutions in the space.

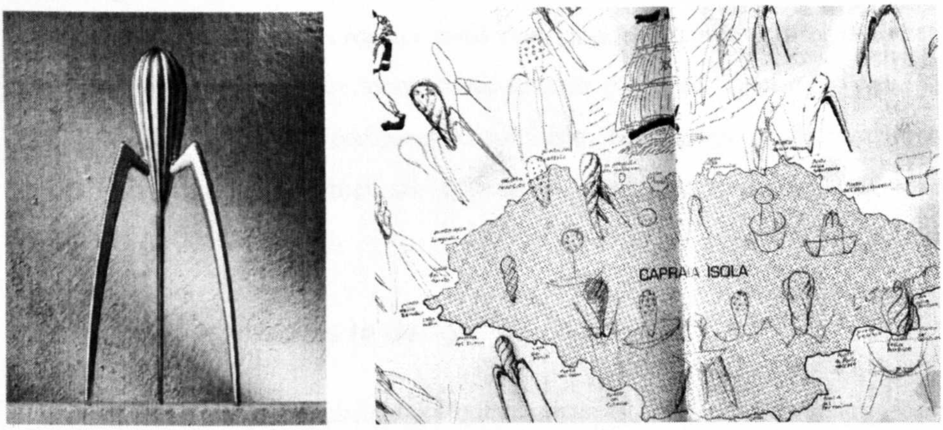


Figure 1.1. Final design (copyright Alessi), and initial sketches generated by Starck to explore lemon squeezers

Observing the sketches in Figure 1.1, one may perceive some sort of connections between their geometries. At the same time, the sources of these connections are hard to identify. These connections suggest that the process of developing designs might trace logical paths from an original idea to a final design. This hypothesis offers a point of departure for considering the development of computer tools to assist the exploration of product design. In order to develop such tools it is necessary to determine the mechanism underlying shape transformation.

This thesis concerns how designs are generated and explored by means of pictorial representations. It makes reference to cognitive processes in designing but it is not an enquiry into the mechanisms of the mind. It presents research into the way designers transform shapes from one state to another using sketch representations. Understanding the mechanisms of shape transformation in design could provide several benefits to design practice and design education. It has been widely argued that computer tools have not supported the creative, exploratory stages of design. While the situation is changing rapidly with the application of new computer aided design (CAD) tools there is still a need for knowledge about design processes where the exploration of shape is paramount, for example, in industrial design. It is now urgent that research in the fields of computing and design cognition make it possible to develop new design tools to be used in these fields. The purpose is not to replace hand sketching, but rather to offer designers computer based tools that are sympathetic to their preferred cognitive styles. By expanding the limits of computer capabilities new shape transformational applications may emerge which are difficult or impossible to perform via other means.

1.2 Formal approaches to design

One way of coming to understand phenomena is through expressing these phenomena in a formal manner. Knuth (1975) points out that the attempt to express knowledge in a formal way can lead to a better understanding than if we try to understand it in a more informal way. By expressing knowledge formally, we are able to manipulate the ideas, reflect on them, and transmit them more effectively (Abelson and Sussman 1990). For example, English grammar formally captures the principles of English language through a set of linguistic rules, which assists us to compose new sentences that can be analysed and interpreted by hearers. In the context of this thesis 'formal' refers to the fact that design actions can be described in terms of rules, and these may assist an understanding of the fundamental principles of design generation and exploration.

Unlike linguistics, design practice has not been provided with a 'dictionary' on which designers can rely to define and express characteristics of their designs. Classic proportioning systems such as the golden section and ratios of proportion, as well as organisational devices like regulating lines, axes, and grids provide good examples of guiding principles, which can be used to formalise properties of design compositions. Several examples can be cited to illustrate the use of guiding principles in design. For example, the ancient Greeks proposed formal theories of harmonic proportions with the aim to achieve visual coherence to designs. Vitruvius designed buildings based upon ratios of proportion taken from the human body. Durer studied human facial proportions by using a construction grid which assisted him to explore and explain variations of human faces through formal descriptions. Palladio, inspired by the Roman principles, offers another good example of using geometric descriptions to achieve harmonic ratios of proportion in architecture. Durand defined a set of design rules with the aim to explain an architectural language in a formal way. Modern designers still make extensive use of guiding principles, albeit less rigid ones. Website designs provide recent examples of using guiding principles as a means to establish a consistency and preserve balance in the design as the content changes.

These examples reveal that designers to some extent use formal descriptions in their processes of design. Formal descriptions can not only be used as a means to prescribe design characteristics but also as a system to assist exploration of ideas (Stiny 2006). Descriptions might be best considered as being produced by application of rules. A drawback to relying on rules, however, is that they are considered to limit the scope for creativity. Most of these criticisms come from those people who understand design rules as a recipe rather than a means to systemize and bring order to a design task. Designing a grid system or establishing regulating lines, for example, also requires creative thinking and form part of the design process. Regulating systems then can be used for analysis and synthesis of designs. Le Corbusier (1931) argued that regulating lines, in addition to other type of formal descriptions, provided him with sources of inspiration. Guiding principles offer to the creative idea a process of composition, a means of interrelationship of form, and a method for achieving visual balance (Elam 2001).

Uncovering how designers employ guiding principles offers a point of departure towards understanding the mechanisms used to generate and explore designs.

While the guiding principles used in architecture are normally straightforward to identify, in product design they are difficult. This does not mean that the process of designing products is less systematic and logical than architectural processes, but might suggest that product designers use different types of principles. An effective way to gain an understanding of how product designers use guiding principles to generate and explore designs is by examining their sketches.

1.3 Research objectives, method, and scope

The goal of this research is to provide a formal model able to generate and explore shapes through mechanisms that are consistent with the processes used to develop product designs. This leads first to examine sequences of sketches that designers produce in creative stages of design and then the opportunities that might exist for computer support. The objective of the presented model is twofold, (i) to demonstrate that designers trace logical and systematic paths in the development of ideas, and (ii) to provide mechanisms for shape exploration that assist the formulation of new computational systems capable of supporting and perhaps even cooperating with designers in the early stages of design.

The technical means that provides the focus for this thesis is the concept of shape grammars. They prove useful in constructing a model for generating and exploring designs in a formal way. Shape grammars are defined by a set of shape rules that make it possible to explicitly convey design requirements. An empirical study is carried out to gain insights into how industrial designers employ guiding principles and explore shapes through sketches. This study identifies common strategies among designers and examines relationships among design sketches generated during creative stages.

This thesis focuses on product design, however, it is argued that the applications of the presented model are not only limited to products but may also include designs from other disciplines such as architecture and graphic design. Although design exploration can be performed in many stages of the design process this research focuses on the early stages, which is when exploration is central. In addition, this research is not much concerned with the final design, but rather it is concerned with the process of design.

1.4 Thesis overview

This thesis is presented in two parts. Part One examines creative processes used in design exploration, and then existing formal systems able to describe these processes. Part Two presents a number of formal mechanisms that assist to develop a model for generating and exploring designs in a systematic manner. Finally, the relationships between the proposed mechanisms and the examined processes are drawn. Figure 1.2 illustrates a diagram of the structure of the thesis.

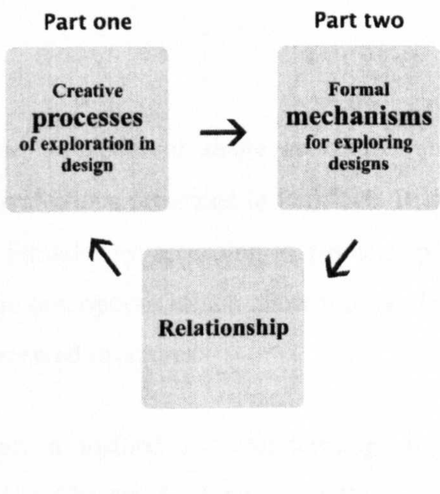


Figure 1.2. Diagram of the thesis structure

The thesis is organized as follows:

Part One:

Chapter 2 examines the role of shape in design, especially in the early stages of product design. Perception of shape is discussed, particularly how this influences the process of generation and exploration in design, and how designers make use of shape through sketches in the design process.

Chapter 3 presents an empirical study that investigates how industrial designers generate and explore designs through sketches. This study provides an insight into strategies for shape manipulation employed during design exploration, and offers a point of departure for broader reflections on the development of design formalisms.

Chapter 4 focuses on the background of computational systems used in design domains. Several branches of CAD systems that have emerged to assist early stages of product design are examined. This chapter explains the functioning of shape grammars and their applications in design.

Part Two:

Chapter 5 proposes a model of shape generation and exploration that is consistent with the observations presented in Part One. It shows how designs can be decomposed in a formal way according to personal preferences. The model presents types of shape descriptions which allow the transformation of the outline of shapes and their perceived structures.

Chapter 6 presents a method for transforming shapes according to the descriptions presented in Chapter 5. First, a simple method for describing and interacting with outlines is proposed. Then, two particular types of rules are presented as a foundation for a model with a broad range of capabilities which meets designers' operational requirements.

Chapter 7 proposes a method to systematically explore design spaces through the generation of design 'families'. These families are generated via the mechanisms of shape decomposition and shape transformation presented in Chapter 5 and Chapter 6 respectively. This chapter shows how formal design spaces can be expanded, contracted, or displaced as design exploration advances.

Chapter 8 analyses the relationships between the mechanisms used in the model presented in Part Two of the thesis and the examined cognitive processes involved in design practice. The model is applied to elucidate the logic in the sequences of exploratory sketches examined in the empirical study

Chapter 9 includes general conclusions and outlines the contributions presented in the thesis. In addition, future work is sketched out.

Part One

Chapter 2

Shape in product design

" If designers use shapes in their work as sketches, drawings, models, and the like, then they can't do anything more than shapes allow. This is a lot for both hand and eye. "

– George Stiny

Overview

This chapter first examines some of the more salient characteristics of the product design discipline and its process of creation. Then, the role of shapes in design is examined, especially in the early stage of product design. It is discussed how perception of depicted shapes influences the mechanisms used to generate and explore concept designs. This chapter focuses on three processes related to perception; first, levels of abstraction, and then, emergence and (re)interpretation.

2.1 Designing: Aims and position

Understanding how people experience and use products is indeed very complex. Partly this is because each individual interprets and judges products differently. In addition, issues like style and fashion act to influence peoples' views towards products. While some people may love a particular design, others may hate it. Present society is becoming more diverse and demanding, and as such improving users experience with products is one of the many forces influencing manufacturers in their gaining of market share.

The industrial designer's goal is to satisfy consumer needs by integrating marketing, appearance, functional, and engineering requirements into one product design solution (Tovey 1989). The importance of each of these requirements depends upon a 'hierarchy of consumer needs' (Jordan 2000), as shown in Figure 2.1, which suggests that once basic needs – such as functionality – have been met, consumers will look for something more. This hierarchy is based on a broader hierarchy of human needs described by Maslow (1970). In the first level of the hierarchy users expect products to perform an intended task or function, that is, products must be functional – note that here, the term 'function' refers to utilitarian functionality as one may argue that aesthetical aspects also accomplish certain type of functions. Once products are successful in function then users will demand products easy and comfortable to use, that is, users will desire usability, that is once products are functional and usable, users will become more demanding and will want pleasurable products that provide emotional benefits.

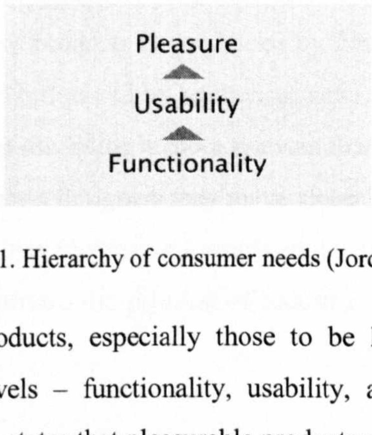


Figure 2.1. Hierarchy of consumer needs (Jordan 2000)

When designing products, especially those to be launched in competitive markets, these three levels – functionality, usability, and pleasure – must be satisfied. Norman (2004) states that pleasurable products really do work better than those without this quality. Certainly, an attractive product is unlikely to be successful if it is not functional, but a functional and usable product may also fail if its emotional values are incompatible with consumerist values. Although functionality is in the lower level in the hierarchy of consumer needs, functionality is not always more significant than pleasure. As Luh (1994) points out, sometimes the aesthetic characteristics of a product may become even more important than its functionality.

Products can have a personality which transfers certain feelings to the targeted consumers. This personality contributes to achieve pleasurable products. They can make people feel happy or angry, proud or ashamed, secure or anxious (Jordan 2000) and this is why consumers are willing to spend money on expensive products even though cheaper products may have similar effectiveness of use. As Norman (2004) claims, designers need to attend to a product's personality by designing all features of the product in accordance to the intended personality. For example, a modern car may exhibit any of a number of personalities such as playful, robust and sporty, and all aspects of the design including functional and aesthetic aspects will be used to communicate the intended personality to users.

Given these intangible characteristics industrial design can be seen as lying somewhere between the disciplines of engineering and art (Gotzsch 1999). While in engineering the form of products is dominated by functional constraints, in art the form is emotional and influenced by aesthetical aspects. Depending on the type of products, however, one discipline is more relevant than the other. In the case of furniture design, for instance, designers may move closer to art whereas in the case of designing a motor car they may move towards engineering. Figure 2.2, based on Gotzsch positioning, illustrates the position of industrial design in between these two fields.

The horizontal axis represents the degree to which the product's form is influenced by emotional and symbolic aspects, and the vertical axis the degree to which it is influenced by (utilitarian) function. Products situated on the bottom-left are considered non-designs because they do not have any functional and emotional and symbolic value. Gotzsch asserts that during the design process, industrial designers switch back and forth between functional aspects of design (related to engineering) and emotional aspects of design (related to art) depending on the type of product and stage of the design process. This suggests that designers are able to attend functional and emotional aspects of designs separately.

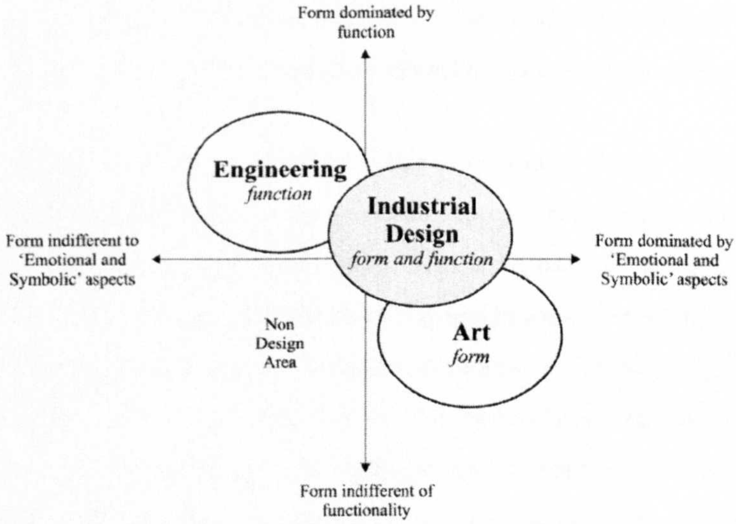


Figure 2.2. Three creation processes and the place of industrial design (Gotzsch 1999)

Shape is a key determinant in design as it is the principal means in which people experience functional and emotional aspects of products. Therefore, shape is also crucial in the process of designing products. When talking about design we normally refer to two characteristics: form and function and, to some extent, this is suggested by the statement *"form follows function"* made famous by the architect Louis Sullivan. Not wanting to examine this statement, because it is open to many interpretations, and independently on whether form follows or precedes function, it is apparent that function of products depends on form. In other words, while form can stand alone without any particular function, the function of products only appears when it is expressed through form. Returning to Figure 2.2, if a designer develops a design by dealing only with functional aspects, it could be said that the product's form follows function. In contrast, if designers develop a design dealing only with emotional aspects, then the products function follows form. However, designers rarely focus only on one of these qualities, but form and function go hand to hand in the design process. This is suggested by the defined statement *"form and function are one"* made by the architect Frank Lloyd Wright. The point that should be emphasized here is that form, or shape, of products is fundamental in design even when only considering the lower level in the hierarchy of consumer needs. In this thesis, the contour of products is referred to as 'shape' (usually related to 2D representations) instead of 'form' (usually related to 3D representations).

This chapter focuses on the role of shape in product design. When talking about shape this thesis refers to the pictorial representations of product's shape rather than the physical shape of products. This is because, in general, designers generate and explore designs through shape representations – especially depicted in drawings. The next section examines the design process in the early stage of design where shape exploration is central. Section 2.3 discusses several issues of visual perception in relation to design and highlights two properties of shapes that are processed at different levels of abstraction. Section 2.4 examines two significant cognitive processes in design exploration: emergence and (re)interpretation. The last section raises important issues to do with the relationships between sequences of depicted shapes in terms of abstraction, emergence, and reinterpretation.

2.2 Conceptual design

Investigations into design practice have motivated many researchers whose main concern has been to capture patterns in the design process. These patterns, which assist in the development of design methodologies, suggest that the design process can be divided into various stages with different tasks in each one. Alexander (1964) claims that breaking down complex problems of design into smaller ones assists designers to tackle design problems in a logical way. Several authors have proposed different methods which divide the design process into stages. These methods are similar in that the phase where exploration of designs is performed with more intensity is located in the early stage of the process (Cross 1994).

Models of the design process are often illustrated using a flow diagram with a sequence of stages. The process generally starts with an initial need or motivation, and ends with the necessary information, such as drawings or construction plans. Every stage is often repeated several times and sometimes feedback loops between stages are necessary in order to continue the process. Figure 2.3 illustrates a model suggested by French (1985). The circles symbolize stages achieved and the rectangles represent different tasks.

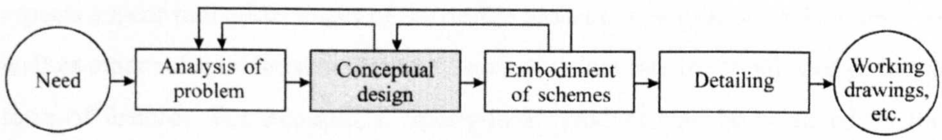


Figure 2.3. Model of the design process (French 1985)

Pahl and Beitz (1984) outline a model of the design process that considers not only the sequence of stages, but also what the output of each stage should be. The first task of the design process is generally 'analysis of the problem', or clarification of the task. To realize the clarification a requirement list should be defined and include the inputs and outputs of the required function of the design. In order to analyse a problem it is often necessary to go one step forward and generate design solutions. This indicates that designers learn about the problem as they generate designs. Often, as Akin (2001) found, designers continue to search for alternative solutions through feedback loops even when they have already developed satisfactory design solutions.

In the second stage, namely the 'conceptual design stage', designers generate broad solutions and, according to French (1985), it is at this point where many significant decisions are taken. This stage can be broken down into: (i) generate an idea, (ii) record the idea – e.g. through visual representations – and (iii) decide whether to continue to generate more ideas or explore the existing ones (Kolli et al. 1993). The stage that follows conceptual design is the 'embodiment of schemes' where selected design solutions are developed in greater detail. French points out that in most cases there is a great deal of feedback from this stage to the conceptual design stage making sometimes the boundaries between both stages not very clear. The last stage of the design process is the 'detailing stage' in which subtle, but no less important, shape features as well as colours and textures of the product are laid down.

As discussed earlier, designing products often involves investigations into emotional aspects with the aim to fulfil consumers' values. In some cases these aspects appear in the late stages of the design process, where emotional values – as well as other values related to pleasure – are integrated into the 'final' design in the form of features. For example, a 'sporty-look' product may be achieved by the application of bright colours or light materials to the product, and these could be realized in the detailing stage. This thesis, however, adopts the approach that aesthetic aspects of design – which are closely related to pleasure – are attended earlier in the process; during the conceptual design stage. The next section returns to this point and examines two different properties of shapes. While one property can be dealt in the late stages of the design process, the other property needs to be attended in the early stages.

The main goal in the conceptual design stage is to come up with promising solutions. Horvath (2000) points out the ideas at this stage are normally vague and therefore the designs outputs, here referred to as *concept designs*, tend to be ambiguous, incomplete, and without much detail. This is not to say that small variations do not have an impact on the concept designs, in fact, small variations are often sufficient to change the essence of an idea.

In order to conceive promising solutions, designers normally generate a concept design first, and then explore the possibilities of that concept (Ward et al. 1995). According to Guildford (1967), when generating concept designs, two types of thinking are used: divergent thinking and convergent thinking. *Divergent thinking* creates diversity in concept designs, which typically occurs in a spontaneous and random way. In contrast, *convergent thinking* displays a focus and is associated with evaluation and modification of one or few concept designs (Liu et al. 2003). Cross (1994) argues that the design process contains irregular intervals of divergent thinking for the purpose of opening the search for new concepts, but in general, the design process is convergent. Thus, the conceptual design stage is a generate-and-explore process in which most of the ideas are connected in some way.

However, the generate-and-explore process itself is not sufficient to come up with promising ideas. It needs creativity. As Boden (1995) notes, creativity is the ability to conceive or recognize novel and valuable ideas. Creative designs provide feasible solutions to relevant problems in new ways. In addition, they grab a consumer's attention and make what Khaslavsky and Shedroff (1999) call 'emotional promises', which means that creative designs arouse an emotional link in consumers towards products. That is, creative designs are likely to satisfy emotional aspects.

Studies of creativity in design have suggested that it is more likely to come up with creative solutions if several alternatives are explored (Cross 1997). Although many factors influence creativity, the processes involved in the manipulation of knowledge are the fundamental means by which people form creative ideas (Ward et al. 1995). Several techniques have been developed with the aim to support creativity by assisting people to manipulate their knowledge. Brainstorming, for example, involves the manipulation of ideas based on different interpretations from people with different past experiences (Kelley 2001). Other systematic techniques such as TRIZ (Savransky 2000) provides solutions to problems from numerous innovative patents and inventions. Although creativity is often seen as a subjective and inaccessible phenomenon, which partly depends on designer's motivations and expertise, these methodical techniques seem to enhance designer's creativity.

Another strategy that a designer may use to stimulate creativity is relying on solutions of previous problems – called design precedents (Pasman 2003). Rarely creative ideas are begun from scratch but they are a mixture of old and new ideas (Ward et al. 1995). Contemporary architects, for example, sometimes base designs on precedent buildings designed by recognized architects (Goldschmidt 1998). Most engineering designs are adaptations or variations of existing designs, or creations of new designs on the pattern of previous designs (Eckert et al. 2000). Design precedents are not only limited to human made objects, products of nature, like the wings of dragonflies or raindrops, can also be considered as design precedents (Thallemer 2004).

One way of stimulating creativity by recalling and processing design precedents is through vision, especially of shapes. Suwa (2005) demonstrates that expert designers are more skilled than novice designers in processing shape from perception. In conceptual design both imagery and visual perception of shapes are often used simultaneously to explore new design alternatives (Goldschmidt 1994). Although both mechanisms are similar (Kosslyn 1990) their consequences may be different. Kosslyn argues that one of the purposes of imagery is anticipating changes or transformations to physical objects. Finke and Shepard's work suggests that there is a cognitive mechanism that integrates mental processes with the physical and graphic exploration of design conjecture. They suggest that designers use imagery to provoke and stimulate perception during design exploration (1986), and some images made for this purpose might consist of very few graphic actions (Garner 2001). While mental images allow exploring designs through the 'mind's eye', visual perception requires the support of visual stimulus. Purcell and Gero (1998) draw up significant implications that visual representations have during design and cognitive processes. They point out that visual representations, especially sketches, support cognitive processes – such as reinterpretation, emergence, and abstraction – that stimulate creativity. This thesis, not wanting to minimize the influence of imagery, concentrates on the visual perception of pictorial representations and its influence in the generation of concept designs.

Once a concept design is generated and perceived, designers try to improve it by transforming the concept. According to Goel (1995) in exploratory stages two types of transformations can be identified; lateral transformations and vertical transformations. The first type, lateral transformations, manipulates one idea into another different idea. They are generated as a consequence of interpreting the idea differently, or generated according to new inspirations that suggest the introduction of new elements. The second type, vertical transformations, clarifies lines and adds detail to an idea while the original version is kept. Vertical transformations are used to generate a range of similar ideas, and occur mainly when designers see an idea as a potential candidate. Shape provides a good foundation to apply both lateral transformations and vertical transformations to concept designs.

2.3 Shape in design

The shape of objects is defined by its boundaries which tend to be perceived through edges and contours (Ching 1998). Ching points out that contours circumscribe objects and define the outer boundary between an object and its background. The shape determined by the contour of an object holds high information content about the object such as aspects of style. For example, the contours shown in Figure 2.4 can easily be recognized as two steam irons, but also the contours allow us to distinguish the style of the two objects, one being classic and the other modern. Attneave (1954) proposed that contours of objects contain high information content, especially in the parts where the contour curvature is higher. That is, the points on a contour where its direction changes more rapidly contain more information than in flatter parts. In designs object contours are depicted in outlines composed of straight lines and curved lines.

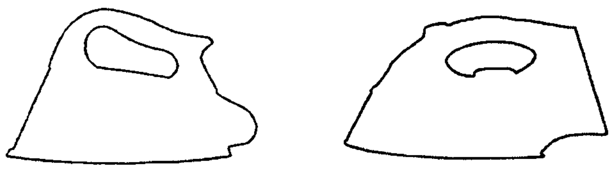


Figure 2.4. The contour of shapes holds high information content

Shape can convey more information about an object than any other properties like colour, material, or texture (Palmer 1999), and this is a possible explanation for why designers make extensive use of shape in design exploration. Another explanation could be that, unlike other properties, shape can stand alone as a representation of an object. Colour, material, and texture can only stand alone as concepts and when they are graphically represented they need to be assisted with the shape. Exploring design through shape facilitates the investigation of crucial aspects of products including style, aesthetics, and function. For example, organic shapes – composed of curved lines – applied to hand-held products are normally associated with pleasurable and easy to use products (Jordan 2000). Emotions can also be transmitted through shape, and facial expressions offer a good example of this. Small variations of the eyebrows or lips contour, for example, communicate whether a person is happy or sad. As with spoken language, shapes are often a powerful means of communication.

Understanding the mechanisms of how humans perceive shapes is a matter of debate. Different theories offer explanations of the phenomena of perception of shapes from different perspectives and sometimes it would seem that they are contradicting each other. The gestalt psychologists undertook one of the major investigations, particularly on perceptual organization (Hamlyn 1961). They identified a number of principles regarding people's preferences in giving structure to perceptions of shapes by grouping their elements. Some of these principles are the law of simplicity – also known as the law of Pragnanz – and the law of closure. For example, Figure 2.5a can be perceived in many different ways (e.g. a set of triangles) but we tend to perceive it as composed of a rectangle and a square. This composition offers a simpler structure than six triangles. Figure 2.5b illustrates an example of the law of closure. It shows that although we see three black circles with sectors missing and three angles, it is likely that one perceives a solid white triangle covering the three circles and an entire inverted triangle.

a) b)

Figure 2.5. Human preferences in perceptual organization

Other major theories argue that perception is based upon past experiences. The influence of the past depends on whether a relation is perceived between the present shape and past experiences. Goldschmidt (1994, p.163) refers to 'clues' as the characteristics that relate present and past experiences, and suggests that *"clues must be able to trigger some relevant information that is stored in the memory but that is otherwise difficult or impossible to tap"*. Arnheim (1974) illustrates the influence of the past in perception through the example shown in Figure 2.6. Such a figure may be spontaneously perceived as a triangle attached to a vertical line.

Figure 2.6. We tend to perceive this shape as a triangle attached to a vertical line

But the perception of this shape may change abruptly when the sequence presented in Figure 2.7 is shown. Now, if we observe again Figure 2.6 it will probably be perceived as a corner of a square about to disappear rather than a triangle. Past experiences influence not only the way shapes are perceived but also the way they are interpreted. Figure 2.7 might be interpreted in many different ways, from an envelope being inserted in a letterbox to a cheese brick being cut with a cheese cutter. These differences in interpretation reflect differences in past experiences, but they might also reflect differences in present need states; for example, hungry people might interpret the square as an item of food because food would be in their minds (Rock 1984). This theory succeeds in demonstrating that past experiences influence the perception (geometric properties) and interpretation (meaning) of familiar shapes, but it does not resolve how cognitive processes operate on unfamiliar shapes. An unfamiliar shape is a shape that has not been seen in the past by the beholder.

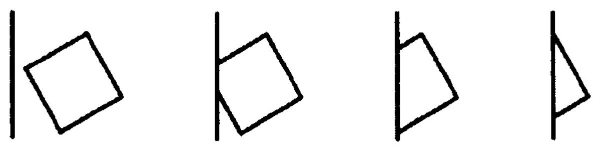
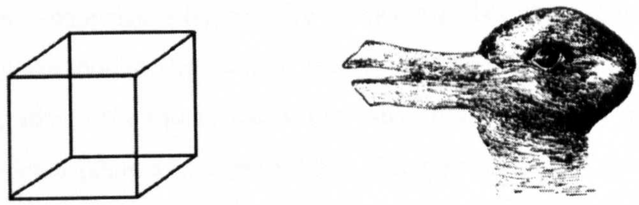


Figure 2.7. This sequence may influence the perception and interpretation of Figure 2.6

What can be drawn from these theories is that they emphasize different aspects of the phenomenon of perception rather that contradicting each other. One of the difficulties of providing a general theory is that shapes can be perceived and interpreted in many different ways. This can be illustrated through the well-known Necker cube and duck-rabbit figures, where both stimuli are ambiguous (commonly) leading to two different percepts. While the changes of perception of the Necker cube can be described in terms of geometry (e.g. orientation of edges and vertices), the changes of perception in the duck-rabbit the geometry does not change (Sloman and Chrisley 2003). What it changes is the functional interpretation of the parts (e.g. 'bill' into 'ears'). These examples suggest that visual perception is to some extent related to shape decomposition.



a) b)

Figure 2.8. (a) Necker cube and (b) Jastrow's duck-rabbit figure (1899)

A wide number of investigations in visual perception have considered the issue of shape decomposition. They are based on psychological evidence that demonstrates that the human visual system uses part-based representations for shape recognition. For example, Hoffman and Richards (1984) argue that decomposition of shapes into elements is useful because even though one never sees an entire shape in one glance, the shape can still be recognized. Bloch (1995) suggests that shapes may first be perceived as wholes, and if these shapes require further processing, then individual elements may become salient. Biederman (1987) points out that in describing objects people tend to decompose shapes into simple volumetric elements because it is easier than to recognize whole complex shapes. To some extent, gestalt theory, which assumes that shapes are perceived as wholes, is opposed to decomposition theories. In any case, the important point here is that at some particular moment shapes are visually articulated by smaller units, here called *elements*.

2.3.1 Levels of abstraction

Another rather different, but not less relevant, aspect of perception is the need to understand why some shapes are perceived as being more pleasant than others. Although perception of pleasant compositions often depends on subjective criteria, there seems to be commonalities among people in judging certain compositions. Psychology and cognate disciplines aim to detect and understand general rules of perception. Arnheim (1974), for example, argues that many people see Figure 2.9a as unbalanced, and therefore unpleasant. Its composition looks accidental, transitory, and somewhat illogical. He points out that the circle is not only influenced by the boundaries of the square, but also by imaginary cross and diagonals that divide the square into symmetrical parts, which he refers to as the *structural skeleton* (shown in Figure 2.9d). The composition is more stable and settled when the circle and the square share the same centre (Figure 2.9b). In general, when the position of the circle coincides with a feature of the structural skeleton it appears balanced. The composition in Figure 2.9c may also be perceived as more balanced than in Figure 2.9a. Wherever the circle is placed it will be affected by the forces of the structural skeleton. Arnheim points out that although visual shapes are basically determined by its outlines, when speaking of shapes we refer to two different properties: outlines and structures. These two properties are processed at different levels of abstraction.

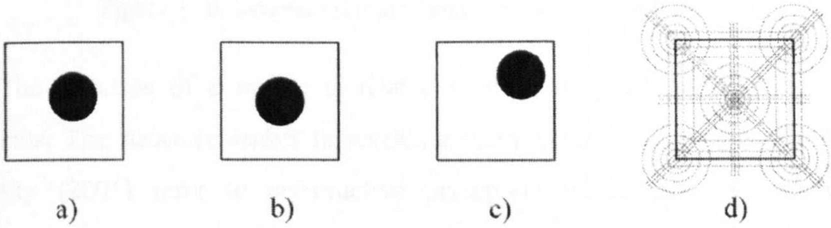
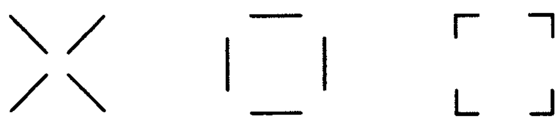


Figure 2.9. (a) Unbalanced composition, (b) and (c) balanced compositions, (d) structural skeleton of the square

In reference of the duck-rabbit example, Arnheim (1974, p.95) asserts that "*this particular drawing allows for two contradictory, but equally applicable, structural skeletons pointing in opposite directions*". This is a possible explanation of why some shapes have more than one percept from one stimulus. Typically, design drawings – particularly sketches – are composed of shape elements arranged relative to each other, and relative to a *reference frame* (Tversky 2001). The reference frame is similar to the idea of structure. Interpreting shapes involves grouping certain elements in a particular way and assigning a structure. Designers are sensible to this requirement when they arrange the elements in a design, and while exploring new designs they seek out the most suitable layouts of perceived elements. One argument in favour of the existence of structure is that some shape transformations lead to refinements of the concept design whilst other types of transformations lead to different concept designs (Goel 1995). Therefore, some shape transformations may entail structure manipulation. Stacey (2005) points out the importance of structure in style judgments. Shared structure may appear more important than shared features, for example, Figure 2.10b may be seen as more similar to figure Figure 2.10c than to Figure 2.10a, though Figure 2.10a and Figure 2.10b share similar features (Wilman 1966).



a) b) c)

Figure 2.10. Structure is important in determining similarities

The structure of a design is related to the perceptual organization of its elements. The structure assists in revealing interpretations of designs. Suwa and Tversky (2003) refer to constructive perception which involves organizing perception in the search for new interpretations. A structure can be used to guide the exploration of new designs. The arrangement of structures determines the identity of the pattern to such an extent that a given outline may produce completely different patterns depending on what structure is perceived in the design (Arnheim 1966). Visual perception is dynamic, and therefore, recognition of the structure of objects necessarily involves active participation by the viewer, as for example, proposed by Kepes (1944) for abstract paintings. Reversing figures, such as the Necker cube and duck-rabbit figures, offers a good example of this phenomenon. If we accept that each shape possesses several different possible elements and structures, according to the way the shape is perceived, then shape values, like style for example, depends on an individual way of seeing which differs from other people's way of seeing (Gombrich 1960). At the same time, one person can repeatedly change the ways of seeing, as is the case of designers in creative stages of design (Schön 1983).

In the exploration of new design alternatives, designers modify the elements of the design according to a perceived structure. If structures are 'viewed' as a higher level of abstraction this reduces the complexity of designs and assists in understanding aesthetic properties, such as balance in composition. Designers switch between different levels of abstraction and use abstract models to test design decisions (Hoover et al. 1991). They argue that while making a design refinement, the designer explicitly considers only those design characteristics which are included within the current abstraction. That is, shape refinements are made within the framework of the perceived structure. In the next section the role of perception in design exploration through pictorial representations is examined, concentrating on the processes of emergence and (re)interpretation.

2.4 Exploring shapes through sketches

Goel (1995) points out that designers manipulate representations of the object rather than the object itself. Earlier in this chapter, it has been discussed that the design process generally starts with a list of requirements (e.g. marketing, appearance, functional, and engineering requirements) and ends with specifications of the design and working drawings. Thus, it could be said that the design process is the process of transforming one set of representations (set of requirements) into another set of representations (e.g. sketches). Most of the design reasoning and decision making is done through the construction and manipulation of visual representations, with sketches being the most used during the conceptual stage of design.

The most common form of representing shapes is by delineating their edges and contours through lines. Skilled draftsmen have the ability to represent concept designs with just a few lines and yet they are sufficient to suggest a particular idea.

A few drawn lines can not only determine the identity of an idea but also make it appear as complete (Arnheim 1974).

Several types of drawings are employed in design. Lawson (2004) outlines eight different types: *presentation drawings, instruction drawings, consultation drawings, experimental drawings, diagrams, fabulous drawings, proposition drawings,* and *calculation drawings*. Each of these types has its own characteristics and not all types are used in the same design stage. While some types of drawings are intended to communicate ideas others are used during the individual thinking process. The proposition drawing is perhaps the most vital in the conceptual stage. Their vagueness and ambiguity promote discovering emergent elements which seems to be vital in creative design exploration (Suwa et al. 1999). Design sketches produced in the conceptual stage are not always external representations of internal mental images, but they may be used as a way of supporting thinking, like talking out loud can assist thinking (Smithers 2001). This thesis focuses on proposition drawings, also termed as *thinking sketches* (Ferguson 1992).

Goel (1995) argues that, on the one hand, designers need ambiguous and vague sketches in order to keep options open as a design arises and not to crystallize too soon. But, on the other hand, designers also need to bring a design to a particular solution. In order to guide a design to an end designers frame the design situation by setting its boundaries, selecting particular things and relations for attention, and impose on the situation a coherence that guides subsequent moves (Schön 1988). Thinking sketches tend to change in appearance as the design process proceeds from vague and ambiguous to more accurate. An example of these changes is illustrated in Figure 2.11. The sketches shown on the left are open to more interpretations than the sketches on the right. Generally, designers start with rough hand-sketches and as concept designs become more concrete sketches become more accurate and realistic.

The inspection of sketches may motivate the making of new sketches. According to Schon and Wiggins (1992) exploring designs consists of 'reflective conversation' with visual representations generated in creative stages. Designers proceed by cycles of 'seeing-moving-seeing'. 'Moving' here refers to the decisions made by designers about their interpretations of the visual representations. That is, as designers sketch, and see what has been drawn, they make discoveries which guide further designing. Goldschmidt (1994) notes that designers transform designs in a cyclic manner. Each sketch is interpreted by designers, transforming the previous sketch by adding, deleting, modifying, or replacing certain elements. Therefore, the reflective conversation leads to the generation of a range of related sketches where each concept design comes out from previous concept designs. The processes of emergence and (re)interpretation of pictorial representations seem to stimulate and guide the reflective conversation.

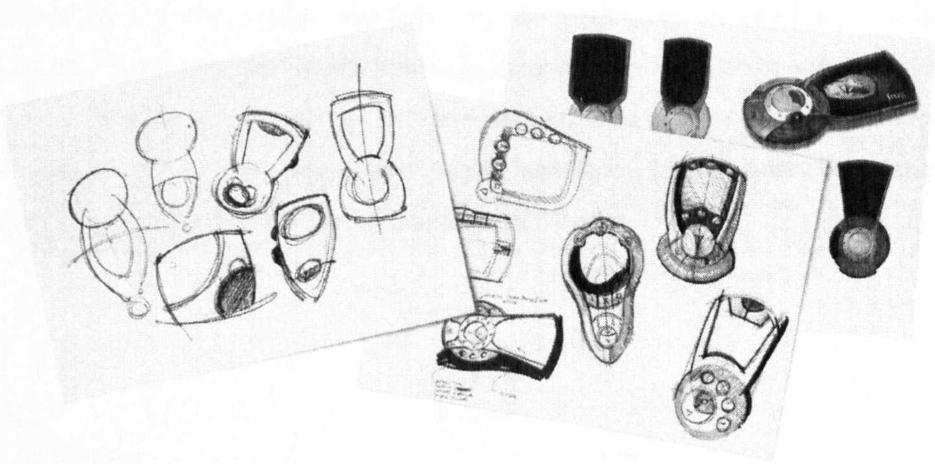


Figure 2.11. Sketches produced in the conceptual design stage (courtesy of www.frogdesign.com)

2.4.1 Emergence

Research on shape emergence has recently gained considerable attention in several fields and is defined as the perception of unintended interpretations, or unexpected discoveries (Suwa et al. 1999). Some researchers have attempted to classify different types of emergence. Soufi and Edmonds (1996), for example, show the difference between emergent shapes that arise as a result of two processes. One is based on emergent shapes associated with *interpretative processes*, and the other one is based on *transformational processes*. Figure 2.12 illustrates two examples for each of these processes. Consider the initial shape shown in Figure 2.12a interpreted as two overlapping squares.

An inspection of such composition may suggest the discovery of emergent shapes. Figure 2.12b shows two examples of emergent shapes, in thick lines, obtained by interpretative processes. In this case the emergent shapes – L-shape and a small square – are embedded in the design. This type of emergent shape has boundaries which are also boundaries of the initial shape. Figure 2.12c shows two examples of emergent shapes obtained by transformational processes, where the emergent shapes – rectangle and a small square – are visually suggested by the boundaries of the design but they are not graphically represented. Similar distinctions of emergent shapes have been suggested by Tan (1990) and Gero and Yan (1994). What it is important in these examples is they reveal that interpretation of designs is not always prompted by visual boundaries, but imaginary boundaries also assist in the process of perceiving emergent shapes.

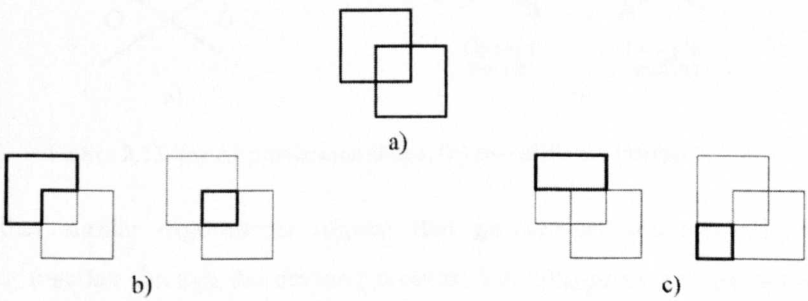


Figure 2.12. Emergence through (b) interpretative process and (c) transformational process

Although the phenomenon of emergence in abstract and simple shapes is well documented in the literature, there is a lack of research on how emergence occurs in sketches used in the exploratory stage of product design. Chapter 3 returns to this point.

2.4.2 (Re)interpretation

Van Sommers (1984) has investigated relations between sketching and vision. His studies suggest that sketches are often segmented into elements and these correspond with the interpreted meaning of the sketch. One of his experiments, concerning perceptual segmentation based on meaning, was accomplished by having two groups of subjects copying designs to which different meanings were attributed by participants. The design shown in Figure 2.13a, was presented to one group of subjects with the title “crossed swords” and the other group with the title “two mice sniffing”. The results were that the two groups duplicated the same design in different stroke sequences. All the people in the first group represented the design by two crossing lines, as shown in the left of Figure 2.13b. In the second group, the majority of people represented the design by two rotated Vs meeting at their vertices, as shown in the right of Figure 2.13b. The rest of the participants represented the design by two crossing lines, similar to the first group, or by using other configurations not illustrated here.

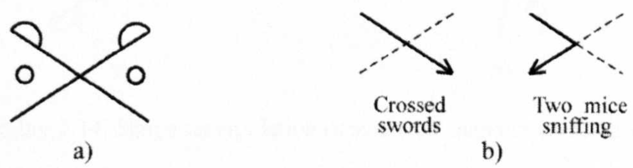
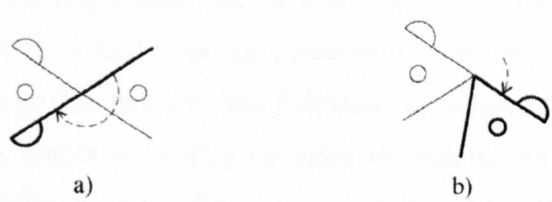


Figure 2.13. (a) An ambiguous shape, (b) two different interpretations

Other similar experiments suggest that geometrical and semantic factors interact together through the drawing process. Yet both processes are not always present during drawing execution. Participants may have a particular semantic intention in their heads which does not correspond to the drawing sequence. As shown in the previous study, some participants that interpreted Figure 2.13a as two mice reproduced the figure by two crossed lines. An explanation of this might be that some subjects considered geometrical factors more relevant than semantic factors. Perhaps, when duplicating the sketch interpreted as two mice, the representation of two symmetrical mice, a precise meeting point between mice, or any other geometric intention was more relevant than semantic factors. In these cases the produced strokes and meaning do not correspond. The more the context requires meaning and the less repetitive the performance is, the more likely it is that semantics will be a greater influence over geometry at the point of action. The study carried out by Van Sommers leads us to assume that in most cases the strokes produced in a drawing are related to its interpretation, and that they correspond with perceived elements.

The assumption here is that manipulation of shapes depends on how they are interpreted and visually decomposed. Thus a set of geometric requirements are imposed presenting uniformity on perceptual preference in sequences of manipulated shapes. Consider, for example, Figure 2.14 which shows two different manipulations of the design presented previously in Figure 2.13a.



a) b)

Figure 2.14. Shape manipulation depends on shape interpretation

The first manipulation, Figure 2.14a, a group of elements (in think line) are rotated by 180 degrees. Such manipulation may be rarely produced if the shape is interpreted as two mice because the transformed shape misplaces the original interpretation. On the contrary, the second manipulation, Figure 2.14b, is more likely to happen if the shape is interpreted as two mice rather than two swords. Moreover, unexpected interpretations may emerge on inspection of the manipulated shape. Observe that Figure 2.14b can still be interpreted as two mice, but now it may be seen as a seesaw. Such interpretation may well be decomposed into different elements. Figure 2.15, for example, marks in thick line the long plank, which is balanced on a central fulcrum.

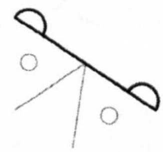


Figure 2.15. New interpretation after shape manipulation

These examples suggest that, first, there is a relationship between the interpreted meaning of a shape and the visual decomposition of that shape; and second, there is a relationship between the perceived elements and their manipulation. This leads us to say that fixation in a particular interpretation constrains the range of possible alternatives during shape exploration. But, what happens when one sees an unfamiliar shape? Is it also visually decomposed into elements?

Earlier, it has been discussed that, as gestalt psychologists pointed out, there are commonalities among people's preferences in perception. For example, back to Figure 2.12a, it is more likely that one perceives it – and also draws it – as two overlapping squares than two L's. Van Sommers investigated the preferences in drawing complex shapes by carrying out some experiments where subjects were asked to copy different shapes from memory. Figure 2.16a shows one of the designs used in the study, referred to as triquetra, and the different strategies used by the participants to reproduce the triquetra from memory. This particular example shows that the participants used common strategies to decompose the triqueta, for example, observe that both the starting and end points of the stroke are in intersection points. In addition, since the design does not have a particular meaning, the decomposition of the shape is driven by geometric factors rather than semantic factors.

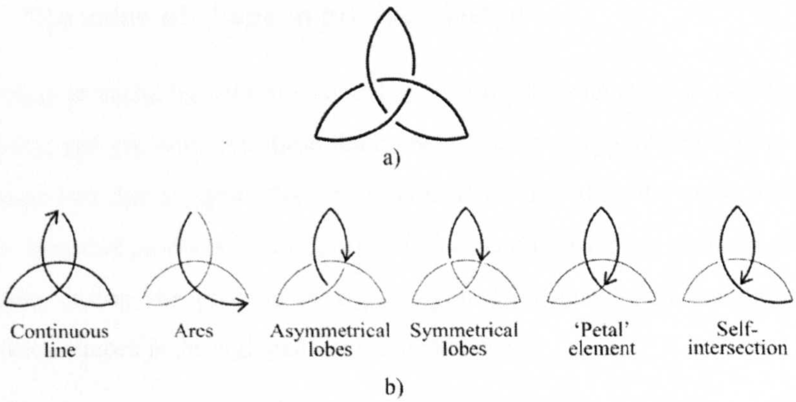


Figure 2.16. Different strategies used by subjects to reproduce a triquetra

Although people can attain more than one interpretation, often once a particular interpretation has been reached, even if it has been achieved with great effort, it is difficult to see other alternatives (Suwa et al. 2001). Interpretation guides the path followed in the exploration process. Revealing how designers interpret their sketches is not easy, however, the study of the segments of sketches and the order of drawing elements gives insight into the mental organization underlying the design (Tversky 1999).

The path leading to the final design cannot be foreseen, and each transitional design generated is a potential turning point where the path can change its course. Understanding how designers perceive shapes assist in understanding the exploration process in design, and understanding how designers decompose shapes into elements is a point of departure in comprehending this process. In the conceptual stage, visual representations tend to be vague and uncompleted which promotes diversity of interpretations among people. Penetrating into designer's reasoning is not straightforward, perhaps unachievable, but examination of their pictorial representations, such as sketches, may give insight into their thought processes.

2.5 The value of shape in product design

This chapter began by outlining some key features of products such as functionality, usability, and pleasure. All these three features are strongly related to the shape of products and this suggests that shape is usually crucial in the conceptual design stage. Shape of products is not only used as an end in itself but also assists creative thinking during the process of exploring new designs. One common way of exploring shapes is through generation of sketches.

Sketched line drawings provide an ideal tool for exploring designs, and it has been used for centuries. Leonardo da Vinci, in the early 1500's, employed sketches using ink and paper to investigate his world and represent his inventions. Nowadays hand sketching is still the most used technique in the conceptual design stage, even in the most advanced design studios. Such sketches are difficult to replace and perhaps there is no need to do so because they already work so efficiently (Blinn 1990). However, improving our understanding of the process of exploring concept designs will bring benefits to design knowledge that can be used to improve the design process. For example, such knowledge can assist in the development of new computational tools that efficiently support exploration of designs.

Depicted shapes stimulate and guide cognitive processes that assist creativity in design. This chapter focused on three processes: (i) abstraction, (ii) emergence, and (iii) (re)interpretation. Understanding these cognitive processes is not easy as they happen in the designers' head, but examining their external representations (e.g. sketches) reveals aspects of their thinking processes. Little is known about cognitive processes in design, in particular those regarding to shape transformations, but many research studies, usually in the form of protocol analysis, have opened up our understanding of design thinking. There is clearly a reciprocal relationship between designer's thinking and their representations. Representations may be a consequence of thinking but also thinking may be stimulated by perception of representations. These connections suggest that explorations might trace systematic and logical paths from an original idea to a final design via sequences of sketches and decisions. One plausible way of relating processes of designers' thinking – including abstraction, emergence, and (re)interpretation – and their representations is through shape decompositions.

Van Sommers (1984) has demonstrated that there is a relationship between interpretation of a shape and the strokes used when sketching that shape. In his experiments, Van Sommers used simple and abstract shapes from which their decompositions are straightforward as shown in Figure 2.13. But, are these relationships between strokes and interpretation also present in product design – for example in reproducing the shapes shown in Figure 2.4? Similarly, examples of emergence and abstraction have been shown through simple shapes such as squares and circles. Do these processes also occur in product design? If they do, how do they operate?

The next chapter presents an empirical study that investigates sequences of sketches generated by designers. The goal is to gain a better understanding of how the three cognitive processes examined in this chapter – abstraction, emergence, and (re)interpretation – influence the sequence of generated designs. It is not so much about the thinking process, but about the mechanisms used in design to transform one shape into another as a means to creatively generate and explore concept design.

Chapter 3

An empirical study of design exploration

" To regard thinking as a skill rather than a gift is the first step towards doing something to improve that skill."

– Edward de Bono

Overview

Chapter 2 reviewed the exploitation of reinterpretation, emergence, and abstraction in design. In this chapter sequences of exploratory sketches produced by industrial designers, against the same task specification, are analyzed in terms of the three cognitive categories reviewed earlier. It is argued that sequences of exploratory sketches – constructed by designer's movements and decisions – trace systematic and logical paths from ideas to designs, which form design families.

3.1 Observing designers

Many studies in this research field have attempted to understand designers' reasoning. Some studies have simply interviewed designers and asked them to explain their design thinking (Cross 2003; Lawson 1994). In others, researchers have studied design thinking from case studies (Candy and Edmonds 1996; Neiman et al. 1999). A more popular approach has been to observe designers while conducting a design task in a lab generally recording them (Goel 1995; Suwa and Tversky 1997; Wang 1998). While none of these techniques alone is able to reveal designer's reasoning, the sum of all of them contributes in constructing a more accurate picture of the processes used in design exploration.

Goel (1995), as noted earlier, observed that, in convergent thinking, two types of transformations occur between successive sketches; lateral transformations and vertical transformations. While lateral transformations are used for widening the problem space by moving from one idea to a different idea, vertical transformations deepen the design by moving from one idea to a more detailed or refined version of the same idea. The use of sketching and sketches can be found across different design disciplines and while the style of sketches may differ the aims and objectives of using sketches are surprising similar (Garner 1990). However, some studies of cognitive processes in design (Akin 2001), and shape cognition (Wang 1998) have identified differences between design disciplines. Wang's studies, for example, found that shape perception tendencies between architects, graphic designers, and industrial designers are different.

Sketches have been used as external representations of design thinking and some findings from protocol analyses are relevant to this study. However, few studies have focused on the investigation of shape relations among sketches. To put it in Schon's terms, most studies have focused on the 'seeing' of designers rather than the 'moving'. The purpose of this study is to explore kinds of moving involved in creative stages of industrial design. This study was concerned with what Ferguson (1992) termed 'thinking sketches' and sought to understand the creative, transformational processes of industrial design. The study set out to investigate how industrial designers generate and explore concept designs, and to analyse the relationships among the constructed representations, particularly where these dealt with product shape. Two questions shaped the inquiry:

- How do industrial designers graphically deal with shape at the conceptual design stage and can similar strategies between designers be observed?
- What relationships exist between representations when lateral and vertical transformations are made?

3.2 Method

There are several techniques to study designer's creative activities such as sketching. One of the most used ones is think-aloud protocol where participants are asked to review and talk through their work. Lloyd et al. (1995) point out that the disadvantage with this technique is that it can result in verbalization that is not a reflection of designing behaviour and that verbalization may affect the designing task. In fact, Lloyd et al. add that if designers could say what they were attempting to do they wouldn't have to sketch it. In order to avoid these side effects, researchers have employed methods of retrospective reporting where participants, while watching a tape recording of their own sketching session, are asked to remember and report what they were thinking as they processed (e.g. Suwa and Tversky 1997). This method requires the session to be videotaped and the participants usually have to work in controlled conditions, for example, having restricted access to external sources. Moreover, the experiments are usually highly time constrained often being completed within one or two hours (Lawson 2004). While the effects of such requirements (video recording, environment and time constraint) might be irrelevant in some investigations, it is believed that they could significantly influence the results in this study.

In this study participants undertook a set task in their normal work or home environment, without being observed or forced to think-aloud, and they had a four week period to complete the task. Participants, therefore, had the possibility of breaking up the task if they wished. The instructions for the task were sent by post and the completed work was returned by post. They were provided with an introductory letter, an A3 drawing sheet with an explanation of the task, and a questionnaire which participants had to open and complete after the task. Although participants were provided with an 'official' sheet on which to sketch their designs they were allowed to sketch additional and personal concepts on extra sheets.

This informal approach was valuable because participants had the advantage of developing the task in their own working places with the minimum pressure; they were not videotaped and they had the possibility of breaking up the sketching process in various phases over the four weeks.

A total number of 8 designers took part in this study. 5 participants were based in different industrial design consultancies. Also there was one university lecturer, one web designer and one design researcher. This was a non-random sample and all the participants undertook the task after previous agreement with the researcher. This sampling method allows the researcher to carry out exploratory research without incurring the cost or time required to select a random sample. All participants had between three and five years experience of professional design practice, including the design and development of various consumer products, packaging and urban furniture. Because of their education and professional experience all participants had proficient drawing skills.

Participants were asked to devise a concept design for a new electric jug kettle. The brief stated that the new design should be composed of organic forms and that it should include a separate base to which the power cord was attached, a water level indicator, an on/off button and a power indicator light. Participants were encouraged to produce at least 10 sketches and to come up with a single and preferred proposal. In order to analyse progression in designing, participants were asked to number the sketches as they created them and they were requested not to erase anything. The fact that participants could sketch in extra sheets allowed them to explore design concepts freely without worrying about the appearance of their sketches. At the end of the task, when completing the questionnaire, participants were asked to submit all documents and sketches produced during the design process including those created outside of the provided official sheet.

The kettle theme was chosen for several reasons. Firstly, kettles are well-known products. Technologically they are relatively straightforward and given the design experience of the selected participants they were unlikely to need to engage in research or investigations in order to generate concept designs. Secondly, kettles are mature products that offer few opportunities for functional innovations. Designers usually rely on aesthetic issues in order to differentiate their product from other kettles in the market. Thirdly, kettles permit designers to pursue new shape opportunities using graphic strategies. For example, some designers may concentrate on the generation of complex curves that outline the external appearance of the kettle, while others may pursue new compositions and relationships between elements.

Once the sketching task was completed, participants were asked to fill in a questionnaire which was divided in two parts. The first part was concerned with the design process, and the second part gathered personal details. One of the questions in the first part, perhaps the most relevant within this study, asked participants to reflect on their generated sketches and, if possible, to place their designs into distinct groupings.

3.3 Observations from the experiment

Each designer produced on average 20 sketches. The least productive participant generated 12 sketches and the most productive generated 71. Where design concepts were represented with two or more views, e.g. plan view and side view, these were considered as one sketch. All participants produced their sketches in monochrome and used ball pens, fine-line pens or pencils.

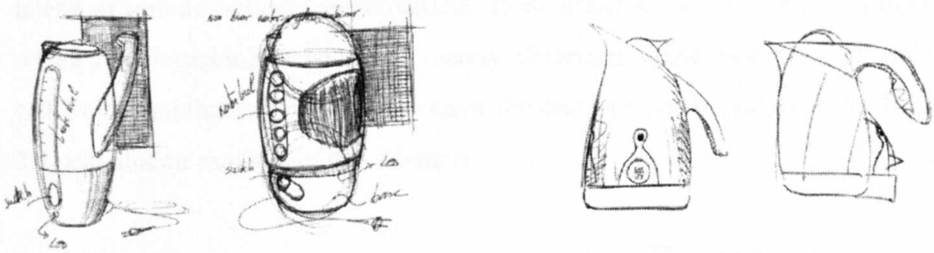
Many sketches produced in this experiment exploited redrawing, where the participant repeated a particular shape or area of a sketch. According to Do and Gross (1996), who refer to this as 'overtracing', it can serve several functions including assisting the selection of, or drawing attention to, an element; the recognition or confirmation of shape emergence by reinforcing particular shape interpretations; and assisting shape refinement, the adding of detail to a basic or roughed out shape. The overtracing of sketches helped a great deal in identifying where participants changed their interpretations and detected emergent shapes.

The complexity of sketches varied enormously, both between participants and within the submissions of individual participants. All participants produced sketches of two dimensional (2D) and three dimensional (3D) views but 2D representations predominated. This might be due to a difficulty of visualising or constructing perspective images of organic forms. Some concept designs were sketched with few lines and no details, others were produced with more detail including annotations, shading or hidden lines. Many participants used brief annotations to their sketches. This was used to indicate, for example, the position of buttons, the material of a specific part of the kettle and also to name parts or concepts, e.g. water drop, bamboo or gourd, thus assisting specific interpretations to the sketches. The annotations of participants were particularly useful in the analysis of concept designs.

After observing the sketches produced by participants it is considered that the main factors that drive the process of design exploration are: reinterpretation, emergence and abstract representations of concept designs.

3.3.1 Reinterpretation

The sketches of most participants reveal variety in the types of strokes used to graphically represent concept designs. As discussed in Chapter 2, Van Sommers (1984) experiments demonstrated that there is a strong relationship between design interpretation and the production of strokes and this study provided an opportunity to examine this. Consider the sketches in Figure 3.1a and Figure 3.1b produced by two industrial designers. The sketches are presented in the sequence they were produced, that is, the sketches illustrated on the right of each pair were produced immediately after the sketches on their left.



a) b)

Figure 3.1. Two sequences of sketches produced by two participants

Figure 3.1a reveals that, initially, the participant produced an outline that encompasses the body and the base of the kettle using continuous strokes. In the following sketch, the participant drew the base and body by separate strokes. This decomposition between body and base appears to give rise to new creative opportunities. Similarly, in the pair of drawings shown in Figure 3.1b the participant initially appears to have constructed the spout and body in one stroke, but in the following sketch, the spout was produced independently from the body indicating a change to the designer's initial interpretation. In the subsequent sketches produced after Figure 3.1a and Figure 3.1b (not illustrated here), the body/base and spout/body were repeatedly produced by separate strokes. Both examples suggest that participants changed their initial interpretation of the design concept by rearranging the elements and changing the structure. The decomposition or grouping of elements influenced the way subsequent ideas were developed offering participants a new range of alternatives to explore.

Similar conclusions could be drawn from the sketches produced by other participants. In most cases, changes in the production of strokes occurred at intersection points; for example, between the spout and body, handle and body, spout and lid. Once participants had visually decomposed their sketches into a particular set of elements, these decompositions were retained while vertical transformations were performed. Generally, changes to interpretation have led to lateral transformation where a design is reframed, potentially giving rise to a new range of alternatives. However, modifications of the original concept can lead to lateral as well as vertical transformations. In some cases it is difficult to distinguish which transformation is which by merely observing shape modifications and in order to reveal that it is necessary to know the designer's own interpretation. Figure 3.2 provides an example of this dilemma.

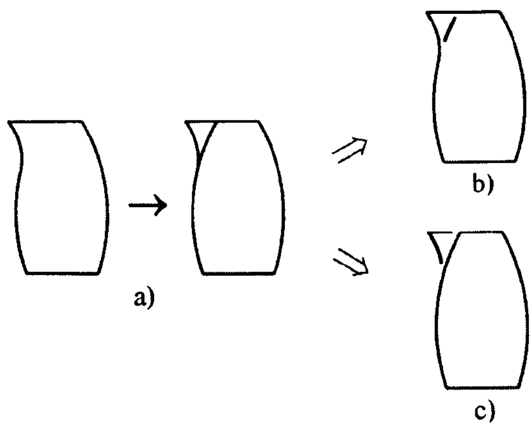


Figure 3.2. (a) A shape modification, (b) modification interpreted as a vertical transformation, (c) modification interpreted as a lateral transformation

Figure 3.2a shows a concept design on the left of the arrow, and its modification on the right. Is this a lateral transformation or a vertical transformation? The answer is that both transformations can be considered. If the interpretation is that a small line has been added to the original concept design, as shown in Figure 3.2b, then it is a vertical transformation because the new line is considered as an insertion of detail to the original idea. However, if the interpretation is that the added line is an extension of the body's contour, as shown in Figure 3.2c, then it is a lateral transformation because this movement leads to a slightly different idea compared to the original version. Moreover, observe that the original concept design cannot be considered symmetric and this lack of symmetry is inherited by Figure 3.2b. However, Figure 3.2c can be seen as symmetric because the spout becomes a detached element from the body.

The designs in Figure 3.2b and in Figure 3.2c are both composed by the same elements (body and spout) as in Figure 3.2a which is the design prior to the reinterpretation. However, reinterpretation of shapes can also lead to the discovering of emergent shapes. Hence, while emergent shapes can be detected in a process of reinterpretation, not all reinterpreted designs lead to emergence.

3.3.2 Emergence

Designers often perceive emergent features in their sketches that may not have been initially intended. As discussed in Chapter 2, such emergence can be based on three types of processes: interpretative processes, transformational processes and regrouping processes. In this experiment five instances of emergence due to transformational processes were identified and three instances arose out of broadly interpretative processes. Since participants explored one single design at a time, no case of regrouping emergence has been found. Only instances that are clear and therefore can be identified by simple observation have been counted. However several questionable instances of emergence were also observed, which suggest that participants recognized more emergent shape than reported here.

The most frequent type of emergence employed by participants was based on transformational processes, where emergent shapes were visually suggested by outlines but they were not graphically represented. Consider, for example, the top row of Figure 3.3 which shows some sketches generated by one of the participants. The second row shows schematic representations of the sketches used as explanatory illustrations. The sketch in Figure 3.3a is a concept design that the participant devised during the sketching process. As the participant revealed in the questionnaire, the concept was inspired by the shape of coffee beans and, at this stage, the participant focused mainly on the external appearance of the kettle. This concept may be perceived as a composition of two elements, as illustrated in the schematic representation. In the subsequent sketch (Figure 3.3b), probably because the designer focused on functional aspects such as the introduction of a lid on the top part of the kettle, a new element emerged. This suggests that the central line of the initial concept has been extended in order to reveal an emergent interpretation. The thick line in the schematic representation outlines the emergent shape. The subsequent sketch, Figure 3.3c, is the result of an alternative interpretation where a new element emerged as a cylinder or sphere, and as a consequence part of the previous shape is replaced by this. In the final sketch, Figure 3.3d, the designer reinterprets an element that was initially present, but which disappeared during the process. The schematic indicates, in thick line, the re-emerged element.

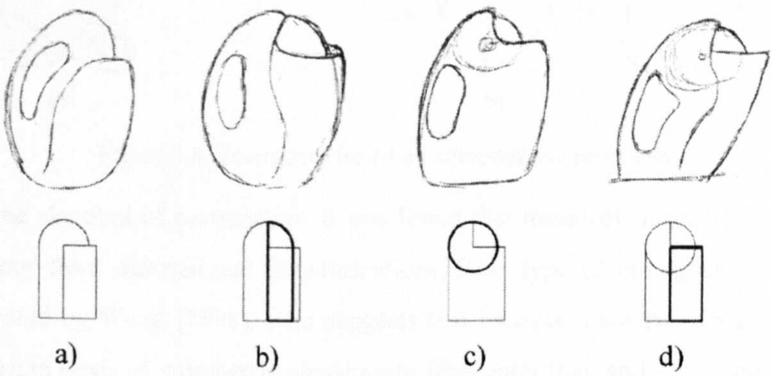
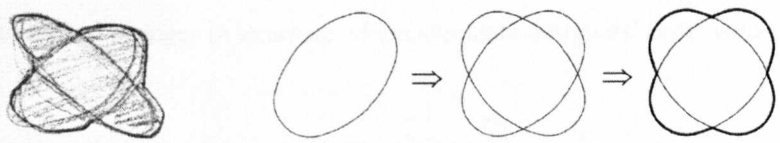


Figure 3.3. (Top row) Sequence of sketches, (second row) schematic representations of the sketches which highlights emergent features

This example suggests how designers take advantage of emergent shapes obtained from transformational processes. Furthermore, it illustrates that the creative process is not a linear process, and that designers explore several alternatives in order to make an improvement.

Another type of emergence employed by participants was based on interpretative processes, where emergent shapes were embedded in the outlines of the design. In this study, interpretative emergence occurred mainly in sketches of low complexity. Some participants initiated the design task by generating several primitives such as circles, ellipses and lens shapes among others. In some cases concept designs were represented with two or more primitives overlapped and intersected. In such cases some participants overtraced the outer boundaries defined by the primitives in order to stimulate emergent shapes. Figure 3.4a shows a sketch produced by a participant and Figure 3.4b illustrates a possible sequence to produce the sketch. The sketch itself, however, does not contain enough information to suggest whether the cross-shape emerged after reinterpretation of two overlapping ellipses or the ellipses were used as a systematic process to construct the cross-shape. Whichever was the case, this simple example illustrates how designers 'calculate with shapes' (Stiny 2006) when exploring designs.



a) b)

Figure 3.4. Emergence based on interpretative processes

In the sketches of participants, it was found that instances of emergent shapes also occur from dimensional transformations. This type of emergence has been investigated by Wang (1998), who suggests that because industrial designers deal with certain types of volumetric shape more frequently than architects and graphic designers a different perception operates. Wang's experiments show, for example, that industrial designers have a strong ability to see the contour of a three dimensional cube when shown line drawings of a hexagon. In the study presented here, one participant began the sketching task by exploring different types of vessels or jugs using perspective views. Initially, the designer considered only revolved volumes, and due to the effects of perspective the circular top section of each vessel was represented as an ellipse. After several sketches, a new concept of kettle emerged based on the repeatedly drawn form of the ellipse. Consider the sketches shown in Figure 3.5 which present the original layout. The numbers in the figure indicate the sequence in which the sketches were produced. Note that the two individual ellipses were not numbered by the participant since he may not consider those shapes as designs.

While the sequence of designs in Figure 3.3 is clearly a result of convergent thinking, the sequence in Figure 3.5 is more dubious since there seems to be no connection between the second and third designs. However, it can be speculated that the egg-like third design has emerged from a dimensional transformation of the spherical qualities of the first sketch idea and the cylindrical qualities of the second idea. That is, the third design is, in some way, connected to the previous designs and the sequence of designs can be considered as a result of convergent thinking. What is most interesting in this example is the fact that certain reinterpretations lead to radical changes in structure which stimulate designers' creativity.

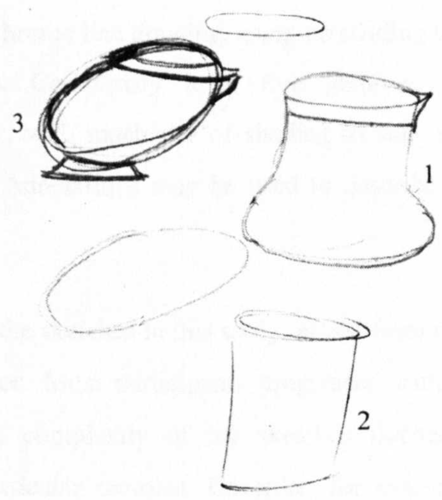


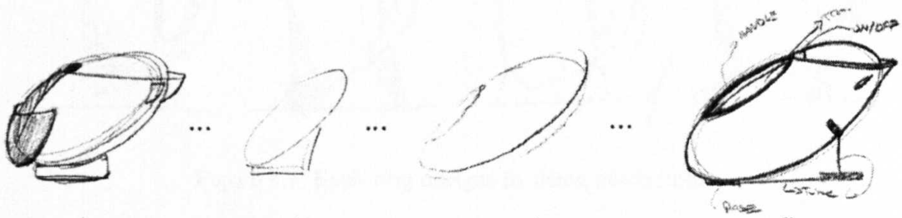
Figure 3.5. Emergence from dimensional transformations

3.3.3 Levels of abstraction

Ambiguous and vaguely detailed sketches are used in the preliminary design phases as well as in the refinement phases. Once designers obtain a promising and detailed concept design, they often step back to higher level of abstractions in order to explore and evaluate the idea from its essence, omitting irrelevant constraints. Liu et al. (2003) discuss three levels of abstraction, namely topological solution, spatial configuration and physical embodiment levels. While in the first and second levels concept designs are represented by diagrams such as 'bubble' charts, in the physical embodiment level, concept designs are represented using shapes.

Through the design process designers generate sketches using different levels of complexity. Generally, there is a correlation between the level of abstraction and the complexity of sketches. The lower the level of complexity in a sketch, the higher the level of abstraction, and vice versa. Here, the complexity of sketches is not measured in terms of shapes but in terms of types of information provided by the sketch. McGown and Green et al. (1998) developed what they termed a 'complexity scale' to measure a sketch's degree of transformation, based on qualitative judgements. The most simple of sketches is rated 'one' and the most complex is rated 'five'. For example, complexity level one involves sketches represented in monochrome line drawing, using no shading to suggest 3D form and no text annotations. Complexity level five involves well-defined sketches represented in colour, with much use of shading to suggest 3D form and many contain annotations. Annotations may be used to describe certain aspects of the idea.

Using this scale, the sketches in this study ranged from complexity level one to complexity level three. Most participants progressed with an oscillating search approach, where the complexity of the sketches fluctuated according to the priorities at each particular moment. Consider, for example, Figure 3.6 which shows a sequence of sketches generated by one participant. The sketches here are presented in the order they were produced, that is, the sketch on the left is the earliest concept and the sketch on the right is the later concept. Note that the participant generated more sketches than those illustrated in Figure 3.6, which are not considered here. The sequence of the sketches reveals an oscillating exploration process, in terms of complexity/abstraction, followed by the participant. Using McGown and Green's scale, the sketches illustrated in Figure 3.6a and 3.6d are rated as complexity level 2, because they have annotations and shading, and sketches in Figure 3.6b and 3.6c are rated as complexity level 1. Although the complexity of sketches varied through the design process the structure appears to be kept, even when abstract representations suggest alternative structures. The sketch in Figure 3.6b suggests that the participant, at that point, was focused on the exploration of bases or supports for the kettle's design. The sketch in Figure 3.6c suggests that the concern was exploring the position and types of handles. These explorations were then further developed in more detail as shown in Figure 3.6d.



a) b) c) d)

Figure 3.6. Exploring designs at different levels of abstraction

Although this example suggests that a single sketch is used to explore a particular level of abstraction, this is not always the case. Often different levels of abstraction can also be used in a single sketch. For example, the use of grids, regulating lines and other types of guide lines are often employed by designers to attend higher levels of abstraction. Guide lines serve to establish and explain the structure of the design since they order relationships and control placement, size, and proportions of selected elements (Ching 1998). Kolarevic (1997) argues that complementary lines become more interesting when they are not only used as rigid skeletons for the construction of design alternatives, but also as dynamic grids. In other words, manipulations of guide lines assist in exploring design alternatives.

Albeit, such complementary shapes are not always represented in the sketch, because they may be constructed, perhaps unconsciously, by the mind of the designer, they still can be considered as part of the structural composition. Figure 3.7 illustrates a sequence of sketches produced by one participant, which suggest that guide lines were used during the exploration process. Observe that some strokes (indicated by an arrow) do not seem to be part of the concept design, but they are complementary lines that assist the designer in defining the handle of the kettle. It can be inferred that these guide lines apart from assisting the designer to frame the position of the handle, they are also assist to the creation of a symmetrical kettle.

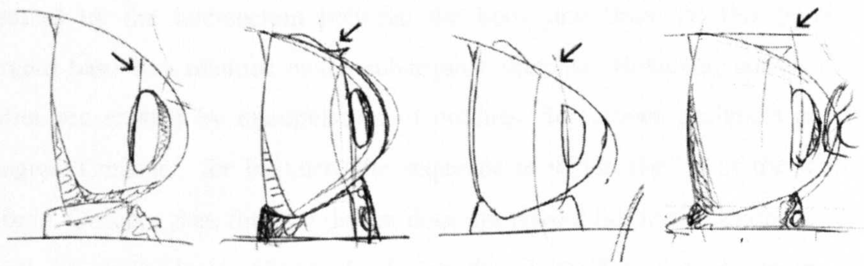


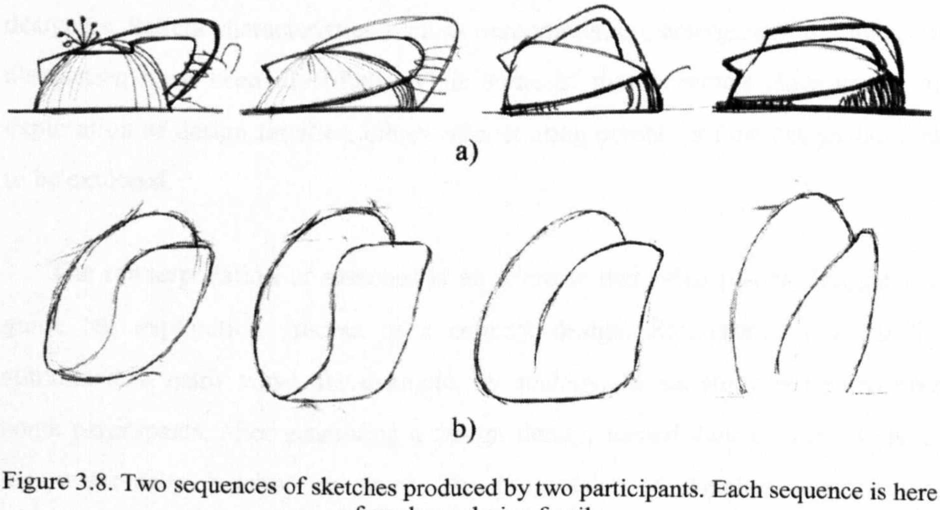
Figure 3.7. Exploring designs by using guide lines

3.4 Design families

The previous section discussed how designers promote creative thinking through a reinterpretation of sketches, emergence, and the exploitation of levels of abstraction. These characteristics appear to be crucial in design generation and all participants in this study made use of them to different degrees. Goldschmidt (1994) argues that designers rarely produce single and isolated sketches, and that more often, they generate sketches in successive spells. While reinterpretation and emergence can give rise to new spells, the use of levels of abstraction is probably more suited to assisting the exploration of spells. Where this works to generate a series of closely related proposals, it is possible to refer to these as a 'design family'. This section attempts to discuss the concept of design families from a practical point of view using the sketches created by participants. Later, Chapter 7 revisits this concept and formalizes it by using generative descriptions.

In practice, designers rarely apply one type of transformation at a time, but lateral and vertical transformations may be carried out concurrently in just one movement. Consider again Figure 3.7 which illustrates a design family. Note that the designs are presented in the sequence they were generated, but the original arrangement has been modified. This sequence of designs suggests that the participant was concerned with the curves that characterize the outline of the kettle as well as with some functional details. Consider now the sequence in which the base of the kettle has been explored. The upper part of the first base is represented with a convex curve, which is then replaced with a concave curve perhaps suggested by the intersection between the body and base. At this point, the emergent base was retained in the subsequent sketches. However, not all design families are created by manipulation of outlines. Sometimes designers combine strategies. Consider, for instance, the sequence in which the lid of the kettle is explored. Observe that, the first design does not have a lid, in the second sketch a lid with a lever has been added to the design, then, in the following design the lever has been removed, and in the last design only the lever has been considered.

Figure 3.8 shows two more design families. The first design family, Figure 3.8a, suggests that the participant was mainly concerned with the handle of the kettle. Observe that the body of the first kettle has a line that represents the lid, and then, in the following sketch, this line has been replaced by another one that represents the base. Interestingly, this criterion, or frame, is kept during several subsequent designs.



a)

b)

Figure 3.8. Two sequences of sketches produced by two participants. Each sequence is here referred as a design family

The design family shown in Figure 3.8b has been generated from a higher level of abstraction. Observe that the sketches do not have any great detail which suggests that the participant, at this phase, was focused on the global appearance of the object, perhaps paying little attention to functional issues. In this design family the participant framed the problem of stability – of maintaining an upright equilibrium – by adopting the strategy of flattening the bottom part of the kettle. Also, as the exploration process advanced, the vertical axis of the object became more perpendicular to the base. These design families reveal that minor variations to curves can produce a significant impact on the appearance of the design.

3.5 Summary

One purpose of this study has been to explore shape relationships among concept designs generated in creative stages of industrial design. Previous studies (Cross 1994; Goel 1995; Goldschmidt 1994) have suggested that, in creative stages of design, designers spend much time exploring designs based on relatively few kernel ideas. Most concept designs produced in creative stages are, in some sense, related and there is much evidence for the existence of close groupings of ideas or design 'families'. In order to investigate shape relationships among designs this study analysed a series of sketches produced, largely, by professional industrial designers. Salient characteristics such as reinterpretation, emergence, and levels of abstraction have been identified. While some of these characteristics assist the exploration of design families, others offer starting points for new design families to be explored.

The reinterpretation of sketches is an exercise that often assists designers to guide the exploration process of a concept design. Reinterpretations can be stimulated in many ways, for example, by analogy. In the study presented here some participants, after generating a design family, named their concept designs; e.g. water drop, bamboo or gourd. The progression of sketches suggests that participants did not have the associated name in mind before producing the sketch and that a reinterpretation of the sketch prompted the analogy. The sketches generated after naming the concept design display more similarities with the analogy than previous sketches, thus, the analogy perhaps served as a guide to participants in exploring further designs. This idea of reinterpretation goes hand to hand with the idea of framing suggested by Schon (1988), where designers impose sets of descriptions on a situation that will guide subsequent moves. That is, when designers consider one particular interpretation they are actually dismissing possible alternatives. Hence, changes of interpretation assist the opening of exploration process by considering alternatives that can only be reached from certain interpretations. How a particular design is interpreted determines whether a subsequent movement will be a vertical transformation or a lateral transformation, and therefore it determines whether a design family will be further explored or if will initiate a new design family.

In the experiment presented here three types of emergence has been observed; transformational, interpretative and dimensional. Emergence originated by transformational processes has been the most used among participants. Although this type of process might be more difficult to foresee, and the range of possible interpretations is much higher, than interpretative processes, it is not less logical and systematic than other types of emergence. Detection of emergent shapes provides points of departure for exploration of new design families.

The perception of sketches at different levels of abstraction appears to be common among designers. In this experiment participants produced sketches with different levels of complexity. Often participants produced sketches with low complexity levels after generation of more detailed sketches of the same concept design. This suggests that designers attend particular concept designs from both higher levels of abstraction and lower levels of abstraction in an iterative manner. On the one hand, exploration of local details may influence general structures of a design, but on the other hand, changes on the structure may also influence details. The perception of designs at higher levels of abstraction promotes changes of interpretation that may lead to new design families, though this has not been the case in this study.

While the participants in this study appear to show no evidence of fixation, in the sense that they produced a varied number of concepts, it is observed that participants used several personal features in their sketches which are applied repeatedly during the process. For example, one participant drew a background to several concepts, or another participant highlighted the inner part of each kettle's handle. This suggests some degree of fixation on certain issues. While this may not constrain designers in exploring creative concepts, it does influence the appearance of the sketches. These fixations, which appear and recede across the sketching process, offer a starting point for exploration of style.

This study has broadened the understanding of the role of design families in industrial design. It has been shown that generation and exploration of design families is often a systematic and logical process. Finally, it has been suggested that designer's moves are highly influenced by their interpretation of the design. Therefore, computational tools that aim to assist generation and exploration of designs should take into account designer's interpretations and reinterpretations that may emerge through the designing process.

Chapter 4

Systems for representing and describing shape

" If we accept, ..., that designers sketch because they want to explore rapidly the possibilities and opportunities that arise in a specific design context, a very interesting motivation for experiment with computers emerges: can computers offer alternative means for the exploration of possibilities that can be used parallel with sketching or, if they prove superior, may replace it at times? "

– Ulrich Flemming

Overview

This Chapter examines the emergence and application of CAD systems that aim to assist design exploration. Such computational systems have the ability to describe and transform shapes in explicit manners which provide the basis for the development of generative descriptions. This chapter presents a number of the authors' own projects which seek to demonstrate the applications of shape grammars to design. The conclusions suggest that not only do new types of rules make shape grammars applicable in product design but they can make a significant contribution to the creative generation of designs.

4.1 Representation and description

To understand the mechanisms of shape exploration in design it is necessary to find an adequate system for representing and describing shape transformations.

Revealing the shape transitions in changing concept designs may give valuable insights into the mechanisms of design exploration. However, there is currently a lack of adequate systems for describing shape transformations, at least in product design. Broadly speaking, such a system should be capable of: (i) dealing with visual representations, since they are the most common form of representation in product design, and (ii) describing shape information provided by representations explicitly. At first glance these requirements seem contradictory because, unlike verbal and numerical representations, visual representations lack primitives and therefore it is less easy to describe them explicitly. This chapter examines current systems that satisfy one or both requirements and propose how more efficient systems could be developed.

As discussed in Chapter 2, visual representations are commonly expressed through sketches and these provide designers with a system to externalise ideas and also, especially in design exploration, to assist design thinking. Visual representations and cognitive processes are interrelated (Suwa 2005). Suwa et al. argue that these connections should be present in some types of computer design tools, as for example, in those tools that attempt to provide opportunities for unexpected discoveries for stimulation of thoughts. In addition, a system is needed that is able to describe shape transformations in an explicit way. One of the difficulties of developing such computer tools is that perception of depicted shapes does not only involve the represented lines, or marks, but also the structure of the shape, which is not visually represented in depictions. Hence, two types of description have to be taken into consideration when describing shape transformations; one type entails represented lines and the other one abstract structures.

A system for describing shape transformations has two functions, to provide a tool that can be used in parallel with sketching and to develop new knowledge of design practice. In other words, this system benefits both designers and design researchers. The knowledge obtained through the system may give insights for the development of more powerful systems that again provide more accurate knowledge of the design process. These feedback loops enhance both the design tools and the knowledge obtained. This chapter attempts to identify how more effective systems for describing shape transformations can be developed and will guide the development of a model presented in Part Two of this thesis, which offers a starting point for the construction of a system capable to capture the mechanisms of shape exploration.

In the next section two different systems of representing shape are compared. Section 4.3 focuses on one of these modes and examines several systems for describing shape transformations with emphasis on two rather different systems; one is particularly valuable for describing line transformations and the other one for structure transformations. Section 4.4 argues that computer systems can offer tools to assist design exploration as well as a means for understanding the mechanisms of exploration. Section 4.5 concentrates on the functioning of one generative system, called shape grammars. Finally, section 4.5 argues that shape grammars provide a potential means for describing shape transformations but further investigations are needed if they want to be applied in exploratory stages of product design.

4.2 Modes of representing shape

Designers rely on visual representations to generate and explore design ideas. The mechanisms of visual perception discussed in Chapter 2 and the empirical study in Chapter 3 suggests that there is a reciprocal relationship between designers' thinking and their representations. These representations may be a consequence of their thinking but also may be stimulated by the designers' perception of representations. Designing includes reflective conversation with representations in which designers proceed by seeing, moving, and seeing again (Schön and Wiggins 1992). That is, the process of interpreting, transforming, and reinterpreting sketches.

Usually, visual representations involve shapes made out of straight and curved lines. Sets of lines represent the outline of concept designs. Designers change the properties and spatial relations of these representations as design exploration proceeds. The path leading to the final design cannot be foreseen, and each transitional design generated is a potential turning point where the path can change its course. There are several modes of representing shape and some of these are particularly helpful in representing design such as hand sketches and computer-based sketches.

Hand sketches have many exceptional properties which are difficult to replace by other means. For example, they allow the exploration of ideas in a flexible and economical way. However, hand sketches do not provide easily manipulated geometric models of the shapes they represent. Although this does not present any direct inconvenience to designers, this geometric information may enhance the designer's capacity to store, manipulate, and reflect on their design representations. Hand sketches do not describe shape explicitly and this makes them an unsuitable system; Figure 3.2 in Chapter 3 demonstrates this. Firstly, hand sketches do not expose how designers interpret shapes, and secondly, a shape transformation drawn by hand can be interpreted in different ways – e.g. as a lateral transformation or vertical transformation. By observing a range of sketches we can identify similarities and differences between them but these are difficult to express. One way to explicitly capture the difference between two curves, for example, is by representing them through a computational system.

In recent decades Computer-aided Design (CAD) has become the single most important influence in modern design practice. A wide variety of software and hardware tools have become essential in fields such as architecture and automotive design and it is now rare to find examples of consumer products where CAD has not played a significant role in the design and development process. More recently Computer-aided Industrial Design (CAID) has emerged, primarily as a response to the need for CAD to better support the early conceptual stage of the design process.

Through a variety of new software and hardware tools, CAID has facilitated significant advances to designers' ability to create and transform shapes.

CAID has sought to offer improved support to designers and there have been significant developments in the process of defining the shape of products. Although they provide a means to transform shape in a systematic and explicit way, CAID has failed to adequately address one crucial aspect, which is, the ability to explore design alternatives consistently with cognitive processes.

4.3 Systems for describing transformations

SketchPad, developed by Ivan Sutherland (1963), was one of the first graphical user interfaces. It allowed the user to create drawings on the screen using a light pen, which is similar to a mouse except that the light pen interacts with virtual objects directly on the screen. SketchPad allowed drawing straight and curved lines without using written code. A straight line could be drawn by defining on the screen the initial and the final points of the line. At the same time, it stored explicit information about the drawing (e.g. the coordinates of these two points). One important contribution it made was that the user had the facility to indicate drawing conditions. For example, to make two lines parallel, the user needed only to successively select two lines with the light pen and then press a key. It is considered that SketchPad was the first step towards the now well known Computer-aided Design (CAD).

Early CAD systems were limited to producing drawings on the computer in a process similar to hand drawing. In fact, CAD systems were meant to aid drafting rather than designing (Steadman and Rooney 1987) since their primary aim was to assist the late stages of the design process by increasing the speed and quality of design documentation and design manufacturing. Once the design is represented on the screen this allows changing geometric properties of shapes in a much more efficient way than with drawings produced by hand. One particular feature provided by some CAD systems is the capacity to define shape parametrically. A shape described by means of dimensional parameters can serve to generate a family of related shapes (Steadman et al. 1987). Parametric CAD systems allow defining relationships between the geometry of different parts of a design, in such a way that if one part is modified the related ones will be automatically modified. Hence, to some extent, these relationships defined via parameters reveal aspects of designers' intentions. Such features, among many others, rapidly proved the value of CAD systems for improving productivity and accuracy in the design process when compared to traditional drafting methods. More importantly, computational systems provide more information about shape properties when compared to traditional methods.

Current CAD systems present a wide range of packages oriented to different design disciplines and even to different design stages. CAD systems are used to assist all sorts of design projects including city maps, buildings, gardens, automobiles, engines, clothes, domestic appliances and micro-electronic circuits. There are no limits on the complexity of the shapes that might be represented. In the field of product design several computational systems have emerged such as Computer-aided Industrial Design (CAID) and Computer-aided Conceptual Design (CACD), among many others (Dankwort et al. 2004). Each of these systems generates and explores shapes in different ways depending on the needs of designers and the stage of design.

CAID is an extension of CAD which offers a system for defining the geometry of complex and organic shapes. The main goal of these tools is to facilitate the task of transform 3D virtual models of the design as a means to evaluate the appearance of a proposal through a realistic render. More recent CAID systems have incorporated haptic interfaces in digital 3D modelling allowing designers to experience the sensation of physical representations whilst interacting with visual representations (Sener et al. 2003).

Although CAID systems provide a tool to generate and manipulate shapes of geometric models, they do not fully support the explorative and creative activities in the conceptual design stage. Partly, the outlines of designs are defined by control points and their manipulation can be sometimes time consuming because it requires moving point by point. Also, CAID systems do not support creativity very well because they do not allow changes of interpretation of the design. That is, if a model is interpreted differently it is often necessary to redraw the model, sometimes from scratch. Hence, CAID systems may be useful to describe the movements designers do in detail stages but not in the early stages of exploratory design.

Computer-aided Conceptual Design (CACD) attempts to support the inherent uncertainty and incompleteness in early design exploration (Horvath 2004). Therefore, the development of CACD systems requires a deeper understanding of cognitive processes. Developments towards CACD have been carried out by Van Dijk (1995) who developed a tool for making fast 3D sketches. This tool allows the user to sketch curves using a tablet, while the curve appears on the screen. Modification of shapes is done by re-sketching and therefore, similar to CAID, the movements between one design into another are not explicitly defined. Similar approaches have focused on the interpretation of freehand sketches with the aim, for example, of using sketches as a way to recover graphical information from a database (Gross 1996), or automatic generation of 3D representations from 2D hand sketches (Juchmes et al. 2004). These tools attempt to mimic traditional sketches on paper and enhance certain characteristics of sketching through computers such as visualization of models from different perspectives in 3D.

CAID and CACD systems provide different means for describing the shape of designs in an explicit manner but none of them provide explanations of transformations between shapes. In other words, two shapes can be compared in terms of their geometry but not in terms of the transformational process between them. Chapters 2 and 3 have argued that design exploration entails manipulations of both outline and structure. The next section examines a system that encodes shape transformations of outlines. This is followed by a section outlining a system that encodes structure transformation in a systematic and explicit way.

4.3.1 Outline transformation: FIORES

Investigations of outline transformations in designs have been carried out by the project FIORES (Cappadona et al. 2003; Giannini and Monti 2003) in the EU Information Technologies portfolio which is a collaboration between industrial product designers, computer scientists, and engineers. This project, divided into FIORES I and FIORES II, attempted to capture emotional qualities of products through computational systems. Such qualities were achieved by applying transformations to the represented outlines of the design.

Podehl (2002), who forms part of FIORES, presents a list of common descriptions and measurements of styling terms used by designers to communicate design intentions (e.g. sharp - soft, acceleration, tension). For example, a small radius can be called sharp and a big radius can be called soft, but giving absolute values is less robust than giving the difference between two curves. Hence, the meaning of 'big' or 'small' depends on the sizes and proportions of the curves to be connected. That means that a particular emotional quality cannot be captured through absolute values because these values depend on other curves, or elements, that also form part of the outline. Podehl seeks to define languages for communicating stylistic properties as well as describing transformations of a design in an explicit manner.

The descriptions presented by Podehl, called *modifiers*, are associated with the emotional character of products (e.g. sporty, feminine, aggressive), which can be defined explicitly through the values of each modifier. Thus, making a curve sharper may lead to a more sporty character. These modifiers assist designers to explicitly express how a shape can be transformed in order to achieve a particular – and subjective – emotional characteristic. Figure 4.1 shows how the user adds tension to the middle section of a design by changing through a slider the values of the modifiers. Other investigations have presented similar systems for manipulating shape of digital models interactively (Cheutet et al. 2004; Vergeest et al. 2001).

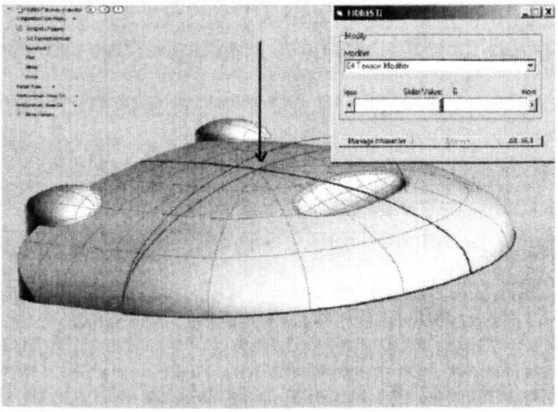


Figure 4.1. The outline of the design is transformed through a set of modifiers (Giannini and Monti 2003)

FIORES displays designs in 3D and surfaces are built out of the outlines. This system allows designers to customize their interpretation of shape character by filling a database. This allows the generation of a family of related designs that preserves a particular emotional character. However, designers can only explore alternatives with a predefined decomposition and structure. That is, the design can only be transformed within a unique interpretation. FIORES does not attempt to provide a tool for exploring different concept designs but exploring small transformations of a particular concept design.

FIORES has demonstrated that it is possible to explicitly capture styling properties through computational systems. These systems assist not only designers to generate design alternatives in a systematic way but also researchers who seek to understand the design process. To some extent, these systems capture designers' intentions and interpretations.

4.3.2 Structure transformation: Shape grammars

Shape grammars (Stiny 1980a) provide a means for describing shape transformations, particularly structure transformation in which sets of shape rules define shape transformations explicitly. Several types of shape grammars have been developed but they can be grouped into three different categories according to their design strategies: (i) grid process, (ii) subdivision process, and (iii) additive process (Knight 1999a).

The *grid* process generates designs within two broad stages. The Palladian grammar (Stiny and Mitchell 1978) shown in Figure 4.2, the Mughul gardens grammar (Stiny and Mitchell 1980), and the Japanese tea-room grammar (Knight 1981) offer good examples of the grid process. In the first stage the grammar begins from an initial shape (Figure 4.2a) and generates a grid (Figure 4.2b) according to defined rules. The grid is comparable to construction lines, which defines the structure of the design. In the second stage the grammar adds the outlines that constitute the design according to the structure and then delete those shapes that may not be of interest in the final design (Figure 4.2c and d).

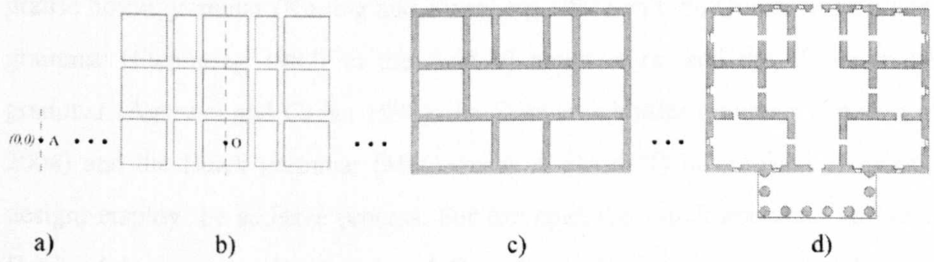


Figure 4.2. The Palladian grammar. (a) Initial shape, (b) grid generated by the grammar, (c) and (d) addition of detail and ornaments (Stiny and Mitchell 1978)

The *subdivision* process is a distinct strategy that is also used in shape grammars. The rules generate designs by making subdivisions to an initial shape. New emerging sub-shapes can be divided successively by applying the same rules. The Chinese lattice grammar (Stiny 1977), the Truss grammar (Shea and Cagan 1999), the Hepplewhite chair-back grammar (Knight 1980) and the Siza's grammar

(Duarte 2005) are some examples that adopt the subdivision process. For example, the initial shape in the grammar that generates chair-backs in the style of Hepplewhite, illustrated in Figure 4.3, is constructed from quadrilateral and triangular shapes. The rules specify how these two shapes can be divided into triangles and quadrilaterals. Similar to the grid process, the first set of rules specifies transformations in the structure and the second set of rules replaces the structure with outlines. This operation changes the appearance of the chair but preserves the generated structure.

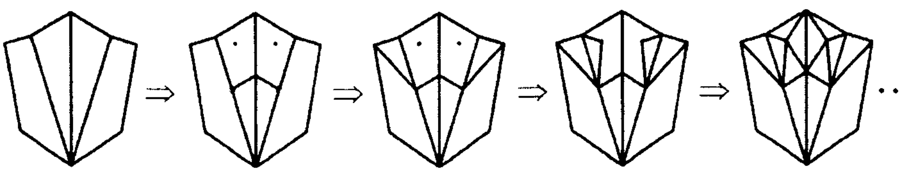


Figure 4.3. Designs generated by the first set of rules of the Hepplewhite chair-back grammar (Knight 1980)

The *additive* process is perhaps the most used strategy in shape grammars, at least in product design. The rules add shapes to an initial shape similar to the grid process but the outlines are added from the beginning. The Frank Lloyd Wright prairie house grammar (Koning and Eizenberg 1981) and the Queen Anne houses grammar (Flemming 1987) in the field of architecture, and the Coffee-maker grammar (Agarwal and Cagan 1998), the Coca-cola bottles grammar (Chau et al. 2004) and the Buick grammar (McCormack et al. 2004) in the field of product design, employ the additive process. For example, the Buick grammar, shown in Figure 4.4, generates front-views of Buick cars starting from an initial shape, which is the centre of the car's grill. Similar to the other processes, the Buick grammar has two types of rules: one type involves structure transformation and the other type involves outline transformation. Unlike the grid process, the structure rules do not define the general structure of the design but the structure of some parts. For example, the Buick grammar has some rules that allow changing the structure of the car's grill but not to transform the general structure of the car.

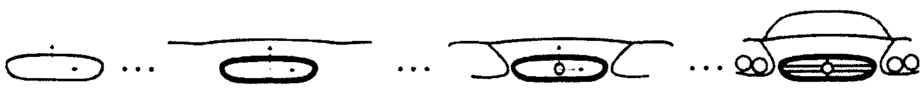


Figure 4.4. Buick grammar. (a), (b) and (c) addition and modification of different outlines of the vehicle, (d) final design (McCormack et al. 2004)

Most shape grammars approaches attempt to generate designs within particular styles or product brands. However, similar to FIORES, shape grammars can also be used to generate designs within particular semantic characteristics. For example, the grammar that generates office chairs developed by Hsiao and Chen (1997), does not focus on a particular style or product brand, but instead on semantic characteristics such as 'comfortable', 'elegant', and 'practical'. Again, a first set of rules deal with the structure of the office chair and a later set of rules are used to transform the parameters of the outline that define the chair.

Typically, the process for developing a grammar is to analyze several designs in the same style, brand, or semantic characteristics, and then define the rules that will reproduce the designs. If the grammar can duplicate the original designs then the grammar is considered a formal description of that language of design. These grammars, however, do not seek to imitate the path traced when the original works were conceived but instead they attempt to explain design works by formalizing the spatial relations of their elements. Thus, the grammar may not correspond to the paths followed by the designer who created the original designs.

The grid process provides a powerful means to explore new structures of designs. Few shape rules can generate a vast, or even infinite, number of designs that are radically different in structure but at the same time they belong to a particular design space. The explorative capacity of the subdivision process is as powerful as the grid process, but it generates less radical designs because the structure is limited to the outer boundary of the design, which is fixed. The additive process, when used in product design, is less concerned with the structure than the outlines of the design. However, the transformation of the outlines is not as clear as the process used in FIORES.

While the three shape grammar strategies generate designs in significantly different ways, they share common characteristics. For example, to some extent, all grammars work first at lower levels of abstraction – the structure description –, and then work at higher levels – the outline description. A distinct example of design generation at different levels of abstraction is illustrated in the generative optimization of building structures (Shea and Cagan 1999), where syntax and semantics are used to model desired relations between structural form and function. Few shape grammar implementations have shown an ability for dealing with different levels of abstraction during the generative process, one exception being the parallel grammar for mechanical designs synthesis (Starling and Shea 2003).

Shape grammars provide a means for defining particular design spaces that can be expanded and constrained according to the user preferences. The literature has shown that shape grammars offer a suitable tool for analysing design works as well as synthesising new solutions within a defined design space. For example, the Buick grammar (McCormack et al. 2004) ensures that the car features generated through the rules maintain the Buick brand. Such a grammar can generate both existing Buick vehicle features as well as novel vehicle features within the brand. Similar to the Buick grammar, most of current implementations provide a fixed set of rules that are developed in advance based on an analysis of precedent designs. Generating designs with these shape grammars the participation of the user is very limited. Users can explore designs within the defined design space but they cannot explore designs outside that defined design space. That is, most current shape grammars do not consider the option of adding, redefining, or deleting rules of a grammar since such actions may violate the language of a defined style, brand, or semantic characteristics.

Most shape grammars attempt to generate coherent sets of designs; however, the free flowing exploratory capabilities of shape grammars have rarely been developed. According to Stiny (2006) shape grammars have wider potential to bridge the gap between early stages of design and modern computational systems. Li (2004), for example, provided students with a shape grammar which they could modify in order to explore new styles of Japanese houses. Shape grammars provide a tool to explain design spaces as well as to explore new design spaces. However, shape grammars are not straightforward to develop. They depend on the skills of the designer or grammar developer.

4.4 Generative design systems

One valuable technique to conceive creative designs is to generate design alternatives. Computational advancements and the evolution of modern design processes have opened new lines of research based on generative systems. Generative design systems can be applied to any stage of the design process but, within the scope of this thesis, this chapter focuses on shape issues. Unlike traditional generative techniques, such as sketching, generative systems generate designs autonomously from predefined descriptions. In general, generative design systems do not attempt to replace designers with computers but to provide a tool that could make design exploration more efficient and creative. The purpose of generative systems is not always to reach a unique optimal solution but instead to display a range of design alternatives.

There are many different variants of generative design systems. They typically generate meaningful and interesting designs starting from little or nothing, being guided by performance criteria within a given design space (Bentley 1999). Computers have proved able to generate and test designs much quicker than humans, and this ability has motivated many generative design studies to use computers to search for optimal solutions to design problems (Mitchell 1996). Another aim of generative design systems is to support creativity. As discussed in

Chapter 2, visual stimulus is an important ingredient to promote creativity, and generative design provides a good foundation for this because it generates several design alternatives quickly. In addition, these systems can generate designs that are difficult or even impossible to obtain via traditional generative techniques. Another and more controversial reason is the use of generative design systems for understanding how design exploration works. While most research on generative systems has focused on optimal solutions, the promise of these systems as a means to support creativity and enlarge design knowledge has yet not been achieved.

It is not difficult to generate a set of designs by computer. What is not easy, however, is getting a set of meaningful designs in a reasonable amount of time. One way of doing this is to generate a set of random designs. Then, select the best designs based on a set of defined constraints, and finally, seed a new generation from the selected designs. This process can be iterated until a competent design is found or the entire design space has been explored. Examples of using this technique include genetic algorithms (Mitchell 1996) and simulated annealing (Shea and Cagan 1997).

However, this approach is not always adequate for the exploration of product designs. As far as aesthetic issues is concerned, there is not a unique optimal design solution, and the 'best' design depends on subjective criteria that is challenging to test by computers. This suggests that most of the testing needs to be carried out by human designers and, since design spaces tend to be immense, the probability of obtaining a satisfactory design in a reasonable length of time is very small.

Another way of getting sets of satisfactory designs is to define design intentions with generation rules. In other words, instead of randomly generating lots of designs and then looking for the meaningful solutions, it is more reasonable to define rules that generate only sequences of designs that are accordant with design intentions. This way of generating designs seems more consistent with natural design exploration. The experiment in Chapter 3 shows that designers rarely generate designs indiscriminately but they frame the generation process according to personal intentions.

Synthesis techniques provide a basis to generate designs through formal descriptions (Antonsson and Cagan 2001). Synthesis is often seen as the task of merely combining existing elements; however, as discussed in section 3.3.2 in Chapter 3, design exploration requires the ability to reconfigure existing elements into new ones. Thus, generative design systems that seek to understand the design process and support creativity need to consider design synthesis in its broader sense. That is, design synthesis should not only rely on the combination of existing elements but also emergent elements should be taken into consideration.

The visual composition of designs is usually of interest to most designers. Two aspects are particularly important in design generation, especially in early stages of design. First, as discussed in Chapter 2, the generative system should be able to produce unpredicted designs as a way to support creativity. And second, the generated designs should provide meaningful solutions, at least for the designer. One plausible way of generating designs agreeable with these two, almost contradictory, requirements – unpredicted and meaningful – is by defining sets of rules in the form of shape grammar. Shape grammars can generate designs that follow the underlying principles of a particular design language, and this language guarantees that the designs generated by the grammar are meaningful (at least for the person who defines the language) even when the grammar displays unpredicted designs.

4.4.1 Languages of design

Artists, architects and product designers talk about languages of design. The writings of Kandinsky, the Russian painter, and Frank Lloyd Wright, the American architect, have been cited as examples (March and Stiny 1982). Present-day designers like Maria da Silva, head of design for the Audi brand group, also talk about languages of design though perhaps in a less grammatical sense (see Audi-

AG 2003). Languages of design assist designers in framing design situations and serve to communicate aspects such as functional and aesthetic characteristics of a design. The form of a simple artefact such as a door handle may inform us whether the door opens with a push, pull, or slide movement. In addition, its appearance may denote different environments such as type of business or life style. Erich Fromm (see Burdek 1994) ironically pointed out that the language of design is the unique foreign language that we all should learn. Languages of design allow us to distinguish Kandinsky paintings from Miro paintings, Frank Lloyd Wright buildings from Le Corbusier buildings, men's suits from women's suits, kettles from steam irons, and so on. Thus, languages of design, apart from telling us how to interact with products, they also transmit many other characteristics of the design including style, brand, and semantic characteristics.

Languages of design are dynamic and subject to cultural pressures for change and development. There is not a universal language of design. At the same time, however, there are some common features that people (within the same cultural and social context for example) understand alike. Designers need to recognize and use these languages in order to connect with the collective of users that the design is intended for, but designers also need to develop their own languages as a means to differentiate their designs from others and grasp the attention of potential users.

Languages of design can be defined as a set of designs based on a common generative principles (Stiny and Gips 1972). Designers, during exploratory stages, consciously or unconsciously create new languages according to their interests and purposes of their designs. This suggests that languages of design are not only useful to explain sets of designs but also are useful to create and explore new sets of designs. One way of obtaining a generative system that is consistent with a particular language is by defining a descriptive language through a grammar or, what might be called a set of rules. Adding, removing, or modifying rules leads to the translation from one language to another language (March and Stiny 1982).

Emile Post (1943) invented a form of computation called *production systems*. They are a model of computation that consists of a rule-based expert system. The rules take the form 'if-then', that is, given a condition A, take action B. In some sense, these rules copy human cognitive processes which involve recognizing a situation, and then taking appropriate action. Production systems were adopted by Chomsky (1957) in the form of generative grammar, namely phrase structure grammars, in order to investigate problems in linguistics. One of his goals was to find common principles to all languages that enable us to produce sentences we have never spoken before, and to understand sentences we have never heard before. Similar to phrase structure grammars, Stiny and Gips (1972) invented shape grammars which generate designs in a language. Instead of using an alphabet of symbols, shape grammars use an alphabet of shapes.

Inevitably, shape grammars have been compared with linguistics, though these comparisons are sometimes erroneous (Flemming 1994). In spoken language, we construct sentences that can be interpreted because they follow a strict grammar of known symbols. Designs, instead, are not composed of sets of known elements with a particular meaning. Unlike spoken language, in which each word has one or few meanings, in design, the meaning of a shape element is open to many interpretations. Languages of design do not attempt to explain meanings of designs but they are used as a means to define particular design spaces. In other words, languages of design do not attempt to reveal the universal rules that generate chairs, for example, but to describe common structures of a particular set of chairs. Once a language is defined further designs that share similar characteristics can be generated.

4.5 Functioning of shape grammars

Shape grammars are based on Post's production systems (Post 1943) and generate formal representations of designs according to a set of shape rules that define design spaces. The first shape grammar, developed by Stiny and Gips (1972), presented a formalism for generating families of geometrical paintings. Their main concern was to use a formal method to generate designs as well as to extend the understanding of aesthetic issues. Such a grammar generates complex compositions from simple geometric shapes and relationships. The 'internal organizing logic' of the generated compositions makes designs aesthetically interesting. Following this idea, early applications of shape grammars were based in the field of architecture. Shape grammars provide a formal framework to explain particular architectural styles and also to generate novel designs within the same style (i.e. Stiny and Mitchell 1978). More recently, shape grammar formalisms have been used in the engineering field to generate designs within a defined design space which can be searched for optimal solutions (Antonsson and Cagan 2001). Also, shape grammars have been used to formalise generative specifications for product brand identity (i.e. McCormack et al. 2004).

Although, to some extent, most generative computational systems exhibit the phenomenon of emergence, in shape grammars emergence is a central characteristic (March 1996; Stiny 1994). Emergence, as discussed in Chapter 2, refers to the perception of unintended features. Some differences between shape grammars and other computational systems lie in the recognition and use of emergence (Knight 2003a). In shape grammars, emergence occurs when a non-predefined shape is recognised and used by the grammar. Thus emergent shapes redirect the path traced by the generative process, and this is comparable to the natural creative process in design. Shape grammars do not only provide a means for generating designs but also offer a tool for aiding thinking. Li (2004) suggests that shape grammars can even enhance our knowledge of how we understand. Stiny proposes that shape grammars are not only useful for understanding but also to work with. He writes: *"The definition of shape grammars is designed to be easily usable and understandable by people interested in generating shapes for visual purposes (e.g, artists) and at the same time to be readily adaptable for the rigorous mathematical investigation of shape."* (1975, p.26)

Typically, a shape grammar is composed of an initial shape and a set of shape rules (Stiny 1980a). Shape rules take the form A → B, where A and B are both shapes, and are applicable to a shape S (e.g. the initial shape) if there is a transformation of the shape A, on the left hand side of the rule that is embedded in S. That is, if A is a sub-shape of S. Shape rules are applied by replacing the transformed shape A embedded in S with the similar transformed shape B, on the right hand side of the rule. Consider for example the shape in Figure 4.5 as an initial shape.

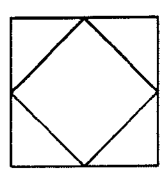


Figure 4.5. An initial shape

This shape can be interpreted in myriad different ways, for example, it can be interpreted as a composition of two squares, four triangles, four Ks, among many other ways. Suppose, however, that it is interpreted as a composition of four triangles and the shape rule shown in Figure 4.6 is defined.

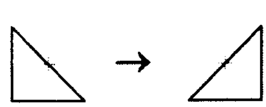


Figure 4.6. A shape rule

This rule replaces an isosceles right triangle with a similar triangle rotated anticlockwise by 90 degrees, and the rotational centre lies on the midpoint of the longest side. Note that the same result can be achieved by reflecting the triangle in the vertical axis. This example shows that shape rules elucidate design intentions (e.g. replace the triangle on the left with the triangle on the right) but they do not reveal the mechanical process to achieve these intentions (e.g. rotation? reflection?). The rule applies when an instance of the shape on the left hand side of the rule is found embedded in the design or when a reflected instance of the shape is found. Because the isosceles right triangle has one axis of reflective symmetry, the rule can be applied in two directions. As a consequence, the rule can also rotate the triangle clockwise by 90 degrees. This 'double application' of the rule can be avoided by using labels, which will be examined in a little while. For now, consider that the rule in Figure 4.6 can rotate the triangle 90 degrees in both directions. Figure 4.7 shows a sequence of designs generated by the successive application of the rule.

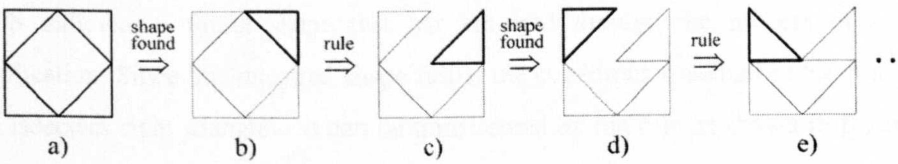


Figure 4.7. Successive application of the rule starting from the initial shape

The thick line indicates the shape that is found and then transformed according to the rule. For example, Figure 4.7b indicates that an isosceles right triangle has been found in the initial shape, and Figure 4.7c shows the result of applying the rule on the embedded sub-shape. The highlighted triangle in Figure 4.7d indicates a new instance found and Figure 4.7e illustrates one possible modification of the found shape. Note that the sequence shown in Figure 4.7 is only one of many possible sequences that can be obtained by using this initial shape and this rule. Figure 4.8 shows a few more designs that can be generated by this simple grammar.

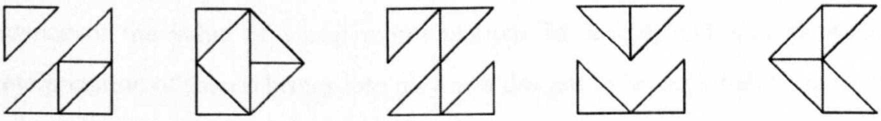


Figure 4.8. Designs generated by transforming the initial shape through the rule

So far, it has been shown that shape grammars generate design alternatives that, to some extent, can be anticipated. In other words, with little effort it is possible to imagine the designs in Figure 4.7 and Figure 4.8 by mentally applying transformations to the initial shape without the help of visual representations. However, designs are more difficult to anticipate if the rule also applies to emergent shapes. Shape grammars have the ability to recognise shapes that emerge during the generative process. Thus, the range of alternatives offered by the grammar is expanded beyond the expected alternatives. Expected alternatives are considered to be those designs composed of the same elements perceived in the initial shape – e.g. four triangles. As discussed in Chapter 2, consideration of unexpected alternatives is a crucial task in creative design. Consider, for example, the sequence in Figure 4.9. The initial shape is now similar to Figure 4.7e. Figure 4.9b indicates a found shape that has emerged through the process of rule application. Since this emerged shape fulfils the conditions specified in the rule – an isosceles right triangle – it can be transformed by the rule as shown in Figure 4.9c. Again, in the new design some unexpected triangles emerge. Figure 4.9d and e indicate an emergent shape and its modification.

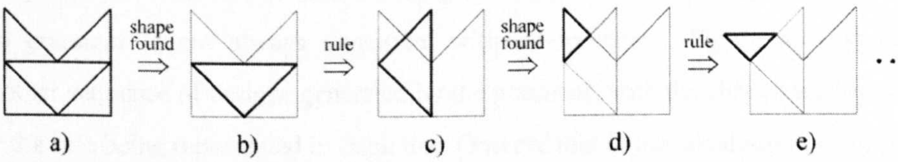


Figure 4.9. Successive application of the rule considering emergence

Figure 4.10 shows more designs generated by the grammar considering emergent shapes. Unlike designs in Figure 4.8, these designs are more difficult or impossible to obtain by applying the transformations mentally. This example gives evidence of the value of visual representations in design, and also shows that reinterpretation of shapes brings into play new designs to be explored. Observe that some of the triangles that composed the initial design have disappeared in Figure 4.10. In Chapter 2 two different types of emergence were discussed – transformational process and interpretative process. Shape grammars only support emergent shapes associated with transformational processes, that is, shapes that are graphically represented in the design. However, section 3.3.2 in Chapter 3 argues that in product design most emergent shapes are based on interpretative processes, that is, they are visually suggested by the outline of the design but not graphically represented. This is a critical issue that needs to be investigated if shape grammars are to be employed in product design domains.

Figure 4.10. Designs generated by the grammar considering emergence

Shape rules provide an easy and powerful way to explore designs consistently with interpretation. The rule in Figure 4.6 is defined after interpretation of the initial shape in Figure 4.5. Therefore, unless the design is reinterpreted, we should expect that the grammar will generate designs that are consistent with interpretation, which in this case are designs composed of four triangles. However, the grammar is not always consistent with interpretation. Figure 4.11 shows another sequence of designs generated by the grammar, with the shape transformed by the rule being represented in thick line. Observe that in the last design one of the triangles has disappeared, or is incomplete. This means that the grammar does not consider the complete design when an embedded shape is transformed by the rule. On one hand this issue allows shape grammars to generate unexpected designs, but on the other hand sometimes designs cannot be generated that may be considered to belong to the grammar.

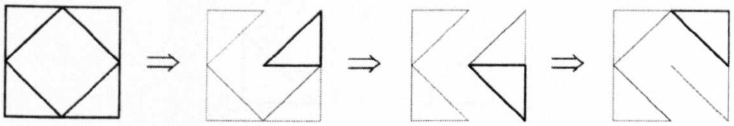


Figure 4.11. Shape rules are not always consistent with interpretation

A design space contains all possible alternatives that can be generated by a grammar. In the above example the design space is defined by only one rule that generates a vast number of different designs. Design spaces can be either expanded or contracted according to users' interpretations and intentions. For instance, adding restrictions on the applicability of rules contracts the design space. On the contrary, inserting more rules to the grammar or redefining existing rules may expand the design space.

Two common strategies utilised in shape grammars are the application of labels and parametric rules. Labels are used for reducing design spaces and parameters for expanding them. For example, the Coffee maker grammar (Agarwal and Cagan 1998) uses both strategies. Labels guarantee that the designs generated by the grammar are built within the required structure (thus excluding designs with different structure), and parameters allow generation of different designs within the same structure.

Usually, labels are represented by points but different strategies can be adopted, such as the use of different colours or line weight. Labels can define where and how rules have to be applied. In order to achieve this, labels need to be specified in the rule as well as in the initial shape. Two similar shapes with different labels are treated differently by the same rule. For example, a label (small point) has been added to the rule shown in Figure 4.12. Note that, in this example, the label is not represented in the shape in the right hand side of the rule, which means that the label will be removed during application of the rule.

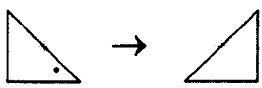


Figure 4.12. Labelled shape rule

Figure 4.13a shows a labelled initial design. Application of the rule is now restricted and only a few more designs than those shown in Figure 4.13 can be generated. These designs can also be obtained via application of the non-labelled rule, but because the design space is immense it may be time consuming before the grammar generates them. Labels assist to specify design intentions which direct the generative process and avoid generation of unwanted designs. The connection between labels and design intentions is further discussed in Chapter 7.

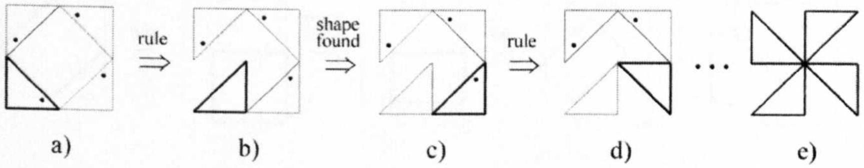


Figure 4.13. Successive application of the labelled rule

Design spaces can be expanded by parameterisation of rules. Parametric shape grammars (Stiny 1980a) are an extension of shape grammars in which shape rules can select a particular condition within a range of conditions predefined by the user. This range of conditions can be defined by parameterizing one or both sides of the rule leading to different consequences. Consider again the initial shape shown in Figure 4.14a. Now suppose that the design is reinterpreted and it is seen as two squares and the rule in Figure 4.14b is defined.

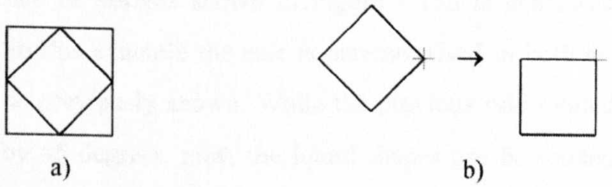


Figure 4.14. Reinterpretation of the initial shape

This rule rotates a square anticlockwise by 45 degrees, and the rotational centre lies on one corner of the square. Such a rule can generate several alternatives if applied to the initial shape. However, if it is considered that the rule is parametric then the number of possible alternatives increases extensively. For example, the shape on the left-hand side of the rule can be considered to be parametric such that it not only represents a square but also all quadrilaterals – such as rectangles, rhombus and trapezoids – with specified conditions, which may be a range of values for lengths and angles of quadrilaterals. Figure 4.15a shows some designs generated by this parametric rule. Observe that during the generative process rectangles emerge which can be recognised in further applications of the parametric rule.

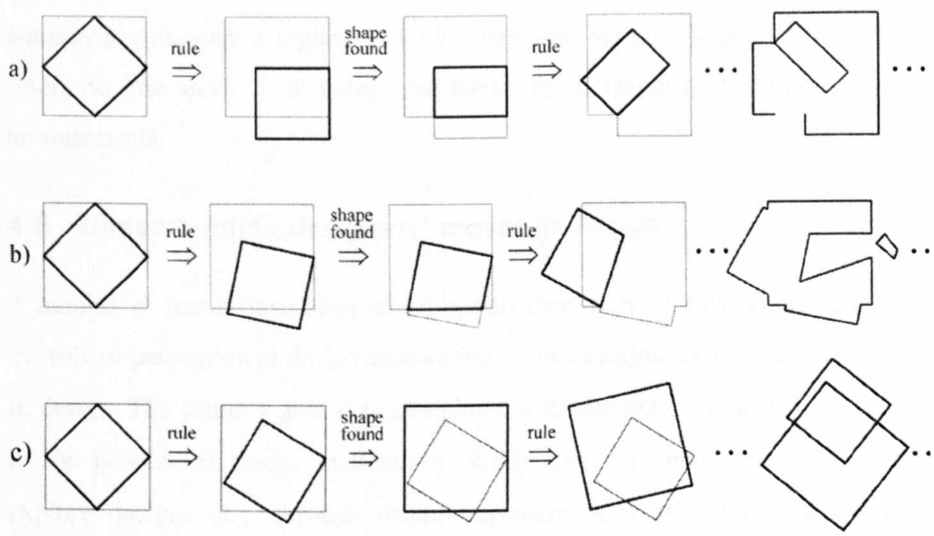


Figure 4.15. Three applications of the rule with different sides parameterised; (a) only the left side, (b) both sides, and (c) only the right side

The sequence of designs shown in Figure 4.15b is generated by a slightly different rule. In this example the rule is parameterised in both sides rather than only one side as previously shown. While the previous rule rotated the square or quadrilaterals by 45 degrees, now, the found shapes can be rotated by any angle within a range defined. Therefore, the design space is newly expanded since a broader range of designs can be generated by the rule. The parameters can also be defined only on the right-hand side shape of the rule (Figure 4.15c). In this case, unlike the other two parametric rules, any possible design will be composed of two squares.

Shape grammars provide a logical way to generate and explore large design spaces through visual representations. One important aspect that makes shape grammars interesting is the organizing framework they provide for establishing spatial relations between design elements. Hence, the designs generated by a grammar possess compositional organizations from rules that possibly make designs aesthetically interesting. Architects, as well as other design professions, often rely on abstract compositional devices such as grids, axes, and regulating lines in order to create logical design compositions; and shape grammars are consistent with such a logical way of composing designs. Logic, in this context, refers to the quality of being justifiable by perceptual principles of shape arrangements.

4.6 Understanding designers' moves in design

A number of issues have been raised in Part One of this thesis. These range from the role of perception in design exploration to the examination of computer systems in design. The primary goal is to examine the fundamental elements that take part in the process of design exploration. While there are many different ways to explore designs (e.g. through mental representations or physical models) this research focuses on one of the most used techniques in design, that is, exploration of shapes through pictorial representations. According to Schon (1983) design exploration consist of seeing-moving-seeing cycles. From this view, in order to gain a better understanding of the process of design exploration investigations into *seeing* and *moving* are required. 'Seeing' refers not only to the process of registering visual information but also implies the construction of the meaning of the visual stimulus. Cognitive processes like interpretation, emergence, and abstraction are strongly related to seeing. In the context of this thesis, 'moving' refers to the set of actions made by the designer to transform a shape into another shape.

These two processes – seeing and moving – are indeed connected to one another. While the process of vision can be investigated in isolation, understanding designers' moves requires considering both processes. The role of seeing in design has been broadly explored and tackled from different perspectives. For example, Goldschmidt (1994) traces the connections between imagery in the mind and visual representations, Oxman (2002) examines the role of emergence in design from a cognitive point of view, Suwa and Tversky (1997) study designers' skills in seeing designs at different levels of abstraction, and Suwa, Tversky et al. (2001) inspect the mechanisms of reinterpretation of sketches. These and other investigations based on seeing contribute to better understand the process of design exploration. However, in order to gain a more accurate picture of design exploration, designers' moves also have to be taken into consideration. To date there is still a lack of studies that concentrate on designers' moves. The sequences of sketches examined in Chapter 3 suggest that designers' moves, in general, trace logical and systematic paths. Capturing designers moves in a formal manner may assist to gain a better understanding of design exploration.

Moving depends on seeing. Therefore, before attempting to investigate how shapes are created and transformed it is first necessary to examine the cognitive processes that underlie design exploration. In Chapter 2 the mechanisms of visual perception and the influence of this perception in the production of sketches have been examined. It is argued that perception of shapes is not only influenced by their graphically represented outlines but also by their structures that are not visually represented. As a consequence, the designers' moves involve manipulations of outlines and/or structures. Chapter 2 argues that shape decomposition, interpretation, and structure are interrelated.

Most investigations into visual thinking have been focused on architectural design. Schon, Goldschmidt, Gross, Suwa, and Tversky, among others, have used architecture students and practicing architects as subjects for their experiments on visual reasoning. Although product design and architectural design exhibit similar visual processes their practitioners seem to possess different visual skills (Wang 1998). In addition, the representations employed in each discipline exhibit different design features (e.g. representations in product design tend to contain more curved lines than in architecture). In order to gain a better understanding of the see-move-see cycle, in Chapter 3 has been analysed explicit examples of how the processes of reinterpretation, emergence, and abstraction are manifested in sketches produced by industrial designers. It has been argued that future computational tools that aim to assist generation and exploration of designs should take into account designer's perceptual preferences – related to reinterpretation, emergence, and abstraction – that may appear through the designing process.

As discussed at the beginning of this chapter, there are many types of CAD systems developed for particular design disciplines and specific design stages. Certainly, CAD systems bring many advantages to design practice, especially in the production of technical drawings as well as realistic representations, but in creative stages most designers still rely exclusively on traditional techniques, like free-hand sketching. This suggests that current CAD systems are still not adequate for the early stage of design. Current computer design tools are not flexible enough to support the dynamism required at these stages, but more troubling, they do not facilitate the constant changes of perception that characterise design exploration. Shape grammars provide a good foundation to support these demands.

Shape grammars have been shown to provide a promising tool for generating design alternatives in relation to seeing and moving. Numerous studies in the literature use the generative power of shape grammars to define fixed design spaces. A design space contains all possible designs that can be generated by the grammar. Design spaces are defined as a means to explain particular languages, such as the Buick language (McCormack et al. 2004) or the Frank Lloyd Wright language (Koning and Eizenberg 1981). In these examples, as well as other similar studies, the grammars are not developed by the authors that created these languages but by shape grammarians who develop the grammar after accurate analysis of such languages. Thus, these developed grammars are personal interpretations of design languages, and therefore the novel designs that these grammars may generate are also subject to the shape grammarians' interpretations. In any case, these grammars do not attempt to capture the original paths traced when conceiving designs in a language but the most comprehensible and straight paths. In other words, their objective is not to capture the design process but the underlying principles of the final design. What is remarkable in these studies is that they demonstrate the capability of shape grammars for capturing design languages and generate in a formal way designs within the language. Flemming writes: *"The interesting question about shape grammars is not whether they should be applied or not in (architectural) design, but why they work so well when they work well"* (1994, p.113).

Unlike these grammars, the research presented here does attempt to capture the design process, particularly the exploration process. The experiment presented in Chapter 3 illustrates that product designers form design families in exploratory stages. The designs that belong to a common family seem to speak a common language, and this suggests that designers construct their own languages of design as exploration proceeds. Although shape grammars possess potential to define rules progressively during the exploration process and not prior to the design task (Stiny 2006), the free-flow exploratory capabilities of shape grammars are rarely developed. Shape rules can be added, removed, or transformed as new interpretations or intentions emerge. However, the existing grammars that are intended for free exploration are limited to rules composed of geometric shapes like squares, rectangles, and triangles. Designs composed of such geometric shapes are more likely to exhibit patterns and emergence due to the simplicity and symmetrical properties of geometric shapes. Thus, the generative process is more likely to proceed. Despite these geometric shapes being too simplistic to be used in design practice, especially in product design, these studies expose the ability of shape grammars of generating designs in a process comparable to design practice.

Shape grammars have shown great potential to be used in design practice; however, there are still some crucial developments to be made. On the one hand, technical issues like shape embedding need to be resolved, particularly on curved shapes (Jowers et al. 2004). On the other hand, grammars with the ability to distinguish between (curved) outlines and structure have not been fully considered. In order to use shape grammars as a means to capture the mechanisms used to generate sequences of exploratory designs, explicit transformation of outlines (e.g. comparable to FIORES approach) and structures are required. Research in this direction bridges the gap between the shape grammar formalism and the process of design exploration. Part Two of this thesis presents two generative mechanisms that challenge existing thinking and provide points of departure for the development of computational tools for shape exploration.

Part Two

Chapter 5

Design decomposition

" The hidden harmony is better than the obvious. "

– Pablo Picasso

" It's hard to imagine a better way to describe shapes than to resolve their parts and to show how the parts are related. This is what decompositions are for. But if parts are fixed permanently, then this is a poor way to understand how shapes work when I calculate. "

– George Stiny

Overview

This chapter is concerned with providing a model to be able to describe how designers identify their individual perception of a shape in the early stages of product development. This is achieved through shape decomposition, which serves as a basis to describe design requirements. Thus, designers can maintain design requirements whilst exploring designs by transforming outlines and structures of shapes through generative rules. A model of exploration is proposed with four types of descriptions: description of contour, decomposition, structure, and design. This exploration presents designs consistent with the individual perception and requirements. The application of generative design methods demonstrates a logical pattern for early stage design exploration.

5.1 Creativity, perception and design decomposition

Creativity includes the generation of ideas as a means of problem finding and problem solving. Suwa (2003) proposes that the coordination of perceptual reorganization and conceptual generation is central to creating novel interpretations and requires particular cognitive abilities. As discussed in Chapter 2, a crucial part of creative activities is discovering new interpretations. A designer may construct a sketch with one arrangement in mind, but on inspection, see another arrangement enabling a new unintended interpretation (Goldschmidt 1994; Schön 1983; Suwa et al. 2000; Suwa and Tversky 1997). These and other studies (for a review see Purcell and Gero 1998) describe how designers use sketches in a range of cognitive processes and the kinds of design ideas that designers generate from sketches. Among many other findings these studies indicate that new design ideas are frequently a consequence of reorganizing and then reinterpreting parts – here referred to as elements – in design representations such as sketches.

In this thesis, exploration of designs is achieved through shape rules acting on (re)interpretations of shapes in sketches. The shape rules serve to transform shapes consistently with cognitive processes. A potential drawback to relying on rules is the view that new designs produced by shape rules in a grammar are not innovative but are implicit in the grammar (Kirsch and Kirsch 1986). However, an alternative view is presented by Stiny (2006), who argues that a strictly generative account of style neglects the new rules and interpretations created and applied as a style develops. The strictly generative account concentrates on a fixed set of rules explaining the final items in a stylistic corpus. The more flexible view of generative design is consistent with the approach to creative design adopted here, where the rules are (re)defined (and discarded) progressively during the exploration process and not prior to the designing task.

A pictorial representation such as a sketch can be perceived in many different ways. Each interpretation leads to a decomposition of the shape into elements with relations among elements (Stiny 2006), which yields a starting point for exploring variations through the generative description. Wide ranging exploration at early design stages seems to depend on being able to jump between interpretations, to develop details within each, and to use these new details to prompt and inspire further interpretation and exploration.

In the model presented here, shapes are decomposed into elements according to how they are visually perceived. Particular decompositions can be used to recognize shapes and analyse their properties. In addition, decomposition of shapes into elements has been widely used by design researchers who seek to understand how shapes are generated in order to develop computational tools that are intuitively usable and understandable by designers. Projects such as FIORES I and II (Cappadona et al. 2003; Giannini and Monti 2002) – refer to Chapter 4 for details – decompose shapes in order to explicitly communicate product aesthetics and aid the development of interactive design tools. In shape grammar implementations, decomposition of shapes has been applied in several forms, ranging from distinguishing shape features, for which separate generation rules are formulated, to hierarchies of subshape types that are subject to different freedoms and constraints on the assignment of parameters (McCormack and Cagan 2002).

This chapter shows that shape decompositions can be described through shape rules which reveal aspects of designers' perception during shape transformation. Although perception is much more complex than simply decomposing a shape, decomposition of shapes is an important part of perception, especially in design exploration. Given the elements in a visual decomposition, a modification applied to one or more of these shape elements results in a new design that is consistent with the designer's original perception.

The model described in this chapter has the potential to enhance designers' creativity through aiding their explorations by transformation and interpretation of shapes. It allows designers to formalize their own perception for each particular shape at any time during a design. This formalization is made through the addition of supporting shapes to the design. These are similar to abstract ordering devices such as grids and composition lines often used by designers that are not part of the physical concept design.

Supporting shapes are here considered to be organized in separated layers of description in a similar way to CAD systems. In a sense these descriptions can also be considered at different levels of abstraction with elements and structure representing higher configurational levels than the physical shape of the outline. The additional layers of description promote new perceptions unintended by the designer, enriching creativity, through exploration of their consequences. An important feature of this process is that the designer has the possibility of exploring new shapes from different views and different levels of abstraction. For example, this accords with practice in early stages of the process when designers constantly move between abstract representations and attention to particular local details. Thus, especially for the early creative stages of product design, it is beneficial to be able to manipulate shapes or shape elements at different levels of abstraction.

Following the discussion above on elements and relations in decompositions, two types of exploration can be immediately identified. These often work together during a design process, but are clearly distinguished here. The first type involves exploration through transformation of the elements perceived in an interpretation. The second type involves the exploration of relations among elements through transformation of structure. In order to deal with these two types of exploration, four different descriptions are presented in separated layers, although one or more layers can be used at a time. Section 5.2 outlines the function of each of the four descriptions. Section 5.3 presents a model for decomposing shapes into elements – through addition of supporting lines – and examines how this may assist designers in exploring concept designs through transformation of elements. Section 5.4 introduces the notion of structures and their application for exploring designs at higher levels of abstraction. Finally, section 5.5 concludes that formal perceptual descriptions are crucial in order to make the computational synthesis process valuable and understandable.

5.2 Four different descriptions for design exploration

One important aspect of the creative process is that shapes can be perceived and represented at different levels of abstraction. During the design process, designers may explore designs at a detailed level by focusing on specific elements of the shape while temporarily ignoring other elements. In addition, designers may explore designs at a more abstract level by focusing on the arrangement of the elements perceived in the shape. Designers often use regulating lines and other supportive shapes to assist the exploration of new arrangements of elements. In the creative stages designers constantly switch between different levels of abstraction. Hoover et al. (1991) argue that, while making a design refinement, the designer explicitly considers only those design object characteristics that are included within the current abstraction.

This is often a mental process and representations at the different levels of abstraction may not be rendered graphically. Therefore, the shape transformations from one sketch to another may not be understood. Two broad levels of abstraction are identified to help formulate the kinds of exploration that occur at the early stages of product design:

- level 1 deals with decomposition, so local details can be explored individually, element by element; and
- level 2 represents the arrangement of elements and thus the structure of the design.

In order to be able to deal with different levels of abstraction separately, layers containing distinct descriptions are employed. Layers separate and locate several pieces of visual information on the same image in an orderly way. For example, a

CAD system may use different layers to place the shape, axis, dimensions, notes, and so on. Different layers can be associated so that a modification applied to one layer may affect associated layers. For the purposes of this research, four associated layers are used: *contour, decomposition, structure,* and *design*. The intention is that layers can be turned off in the model, making the information invisible, and users can explore any abstract level individually. For instance, one might want to concentrate just on exploring new structures, so the other layers can be turned off. Once some candidate structures are found, the design layer can be turned on again in order to see the new designs produced by the new structures.

The *contour layer* is where the outline, often in the form of a sketch composed of geometric elements representing the initial concept design (initial idea for a design), is placed. This layer is used for adding or subtracting elements as well as for introducing a whole new concept design in an informal way – that is to say, without using rules. Two examples are chosen to illustrate the way the model works: abstract geometric designs based on interlocking curves and a functional design representing a jug kettle (Figure 5.1). The explorations observed in a study of industrial designers are shown to closely mirror the types of exploration on these shapes.

Figure 5.1 shows two examples of initial concept designs: (a) a geometric shape composed of three interlocking circular arcs or three petals – recall that this shape, referred to as triquetra in Chapter 2, may be decomposed in several different ways as shown in Figure 2.15 – and (b) the outline of a functional product design (a jug kettle); a shape without crossing lines. Note that shapes with crossing lines tend to be easier to perceive in a variety of interpretations. At each crossing point there is more than one choice.

a) b)

Figure 5.1. Two representative shapes constructed from curved arcs

The *decomposition layer* contains the information of the shape decomposition. It formalizes all the elements identified in the shape and all the constraints applied to them. An element is a piece of the outline of the shape. A shape can be decomposed in infinite ways according to different perceptions. Several different decompositions may be explored at the same time. The decomposition layer is used when exploring variations in the detail shape of a particular element. Although these types of variation often generate similar designs, some variations can lead to a radical change of the whole shape. However, even more radical changes will be consistent with a designer's perception because relations as well as elements can be modified.

The *structure layer* formalizes the interpretation of the grouping and arrangement of elements. The formal representation of the arrangement of elements is again achieved by means of shapes on the structure layer. Rules applied to these shapes change the structure and will implicitly define new parts. In a sense the structure layer contains an abstract view of the whole shape composition. Structures are formed from groups of elements, and several different structures may be identified for a particular shape.

The *design layer* contains the transformed shape of the new design, or group of new designs, and is the source for reinterpretation which may suggest the introduction of new rules, and prompt the redefinition or discarding of the exiting ones. This layer displays what designers would draw in a sketch to represent an idea. Supporting lines that define a particular decomposition or a structure are not displayed in this layer, but only the outlines that are considered to be part of the physical design.

5.3 Decomposition into elements

Decomposing shapes into elements assists analysis and exploration of shapes (Krstic 2005; Stiny 1994). However, the ways that shapes are visually decomposed is often unpredictable, although for certain shapes many people decompose them into similar forms. For example, the decomposition of the shape of a spoon will tend to be decomposed into separate elements (handle and scoop) according to their function. The number of different decompositions of an abstract nonfunctional shape may be higher, but common preferences can be observed. Biederman (1987) argues that human vision tends to perceive shapes as a set of primitives. Singh et al (1999) argues that, if a silhouette can be decomposed in more than one way, human vision prefers decomposing it using *shortest cuts* across the silhouette. Gestalt theory also suggests common perceptual preferences among people, as discussed in Chapter 2. Consider, for example, the logo of the Audi car brand shown in Figure 5.2.

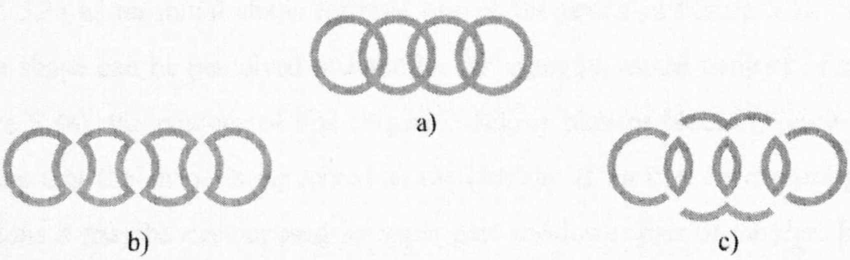


Figure 5.2. (a) An Audi logo and (b, c) two different decompositions. Note that in order to illustrate the decompositions in (b) and (c) the perceived elements are separated from one another

It is a shape that can be decomposed in several forms. Figure 5.2b and c show two examples, but most people would decompose it into four circles, perhaps because of the Gestalt principle of continuity that predicts the preference for continuous shapes such as the contour of the circle. Similarities in decomposing shapes suggest the possibility of decomposing shapes in well-defined ways. However, in the process presented here decomposition is not prescribed or defined beforehand because creative people perceive shapes differently; they 'break' rules of perception in the design process. Rules are used here as a means for the designer to express intentions and generate new shapes that are consistent with perception and intentions.

5.3.1 Definition of the elements

A shape decomposition identifies the limits of each perceived element. The designer might mark the extremes of perceived elements with breaking points or *decomposition points* – which are introduced in the decomposition layer. The decomposition points are placed in strategic places on the contour at perceived points of discontinuity that generally coincide with the intersection of two or more lines (straight lines and/or curved lines), line endpoints or intersections produced by perceptual extensions of lines. Tapia (1999) and McCormack and Cagan (2002) use this idea of points of discontinuity to assist shape matching in their computational implementations. However, sometimes during the design process the decomposition points may also be perceived to lie on smooth curves. Consider Figure 5.3a as an initial shape forming one of the petals in Figure 5.1a. Such a simple shape can be perceived differently, for example, as the contour of an eye (Figure 5.3b), the contour of lips (Figure 5.3c), or blender blades (Figure 5.3d). Suppose that the shape is perceived as the contour of an eye. In exploring new variations it may be decomposed as upper part and lower part of the eye. Hence, the decomposition points illustrated with circles are placed on the two points of discontinuity of the shape (see x and z, Figure 5.3a). During the generation process, the points of discontinuity are kept fixed and the outlines that unify the two points are transformed in order to explore new appearances of the eyes. This decomposition is perhaps the most obvious because it directly uses the two points of discontinuity. Using decomposition points, which do not lie at points of discontinuity, leads to significantly different shapes during modification, as illustrated by the lips or the blender blade in Figure 5.3c and d.

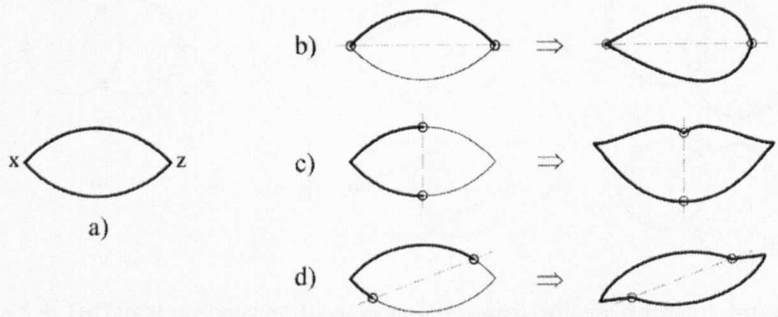


Figure 5.3. Three interpretations of (a) a petal shape using different decompositions: (b) at points of discontinuity, (c) bilaterally symmetric points on the curves, and (d) rotationally symmetric points

The decomposition points are normally placed on the contour line, although exceptions are not precluded and there is no formal limit to the number of decomposition points. The decomposition points identify possible elements in the contour. Each element can be represented by a *decomposition line* that joins the two extremities of each element. Decomposition lines are supportive shapes that assist the formulation of the shape rules, but they are not part of the final design. Many elements and corresponding decomposition lines can be constructed from one set of decomposition points. Figure 5.4b, c, and d show different forms of unifying the same decomposition points in Figure 5.4a. The shapes on the right side of the arrows show possible manipulations of the outlines defined by decomposition points and decomposition lines.

Once the decomposition points and decomposition lines are introduced in the decomposition layer, a new shape appears made of straight lines. This shape, here referred to as a *diagram of elements,* can be considered as an explicit picture or representation of the perceived elements, which indicates where to explore shape transformation of elements and new arrangements of the elements.

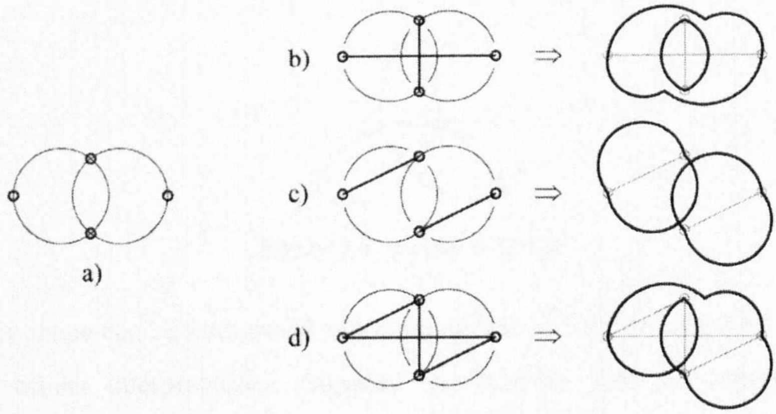


Figure 5.4. Different pairings of decomposition points indicate different decompositions

Figure 5.5 shows different diagrams of elements. The star-like diagram (Figure 5.5a) and the triangle diagram (Figure 5.5b) suggest that the shape is perceived as a balanced composition. Figure 5.5c decomposes the jug kettle shape into four elements, which do not follow any recognizable pattern, and Figure 5.5d decomposes the same shape into six elements following a recognizable pattern. It is possible to give a name to each element: base, front main body, spout, lid, handle, and rear main body of the kettle. This last decomposition was based on functional judgments, whereas the previous ones in Figure 5.5 were more concerned with aesthetic judgments such as balance and symmetry.

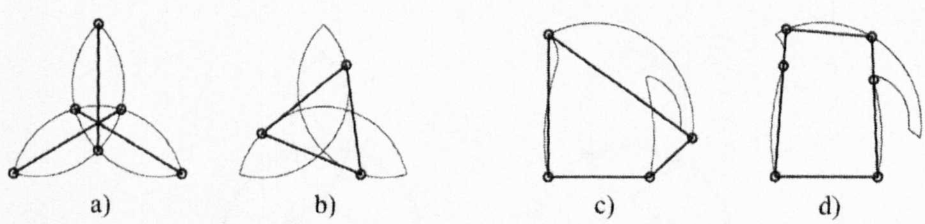


Figure 5.5. Decomposition points and decomposition lines indicating elements

The benefits of decomposition points and decomposition lines are that they can define shape transformations in an explicit manner whilst these transformations are consistent with designers' requirements. This is not always possible when using shape grammars without supporting lines. For example consider the shape shown in Figure 5.6 as an initial design.

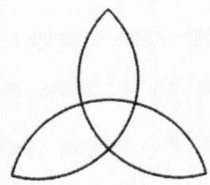


Figure 5.6. An initial design

This shape can be interpreted as a composition of three equal petals overlapped, among others interpretations. Suppose for example that the intention of the designer is to increase the convexity of the outline of all three petals. Here, making the curve more convex is considered as the increment of the area of the enclosed shape. This could be done by defining a shape rule similar to Figure 5.7, where the outline of the petal is replaced with a new outline of higher convexity.

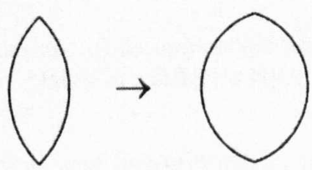


Figure 5.7. Shape rule

After applying this rule to the initial design concept, the result might not turn out as expected. See Figure 5.8.

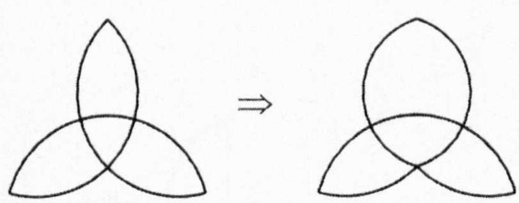


Figure 5.8. Application of the rule to the initial design

This type of rule can only apply the transformation to one petal, but not to all three. The rule is defined correctly. The left-hand side of the rule specifies the element to be attended, and the right-hand side specifies the manipulation of the element. But, the problem is that the rule does not consider all possible interpretations of the initial concept design. Sometimes a personal interpretation could consider 'hidden features' that are not graphically represented, such as overlapping lines – one line in a sketch may sometimes be seen as two or more lines one on top of the other. In order to capture more information through the design process, the decomposition points and decomposition lines are defined. Notice that, in the examples shown here, different line styles are used for distinguishing layers. For example, contour layer is represented with dotted lines and decomposition layer with continuous lines.

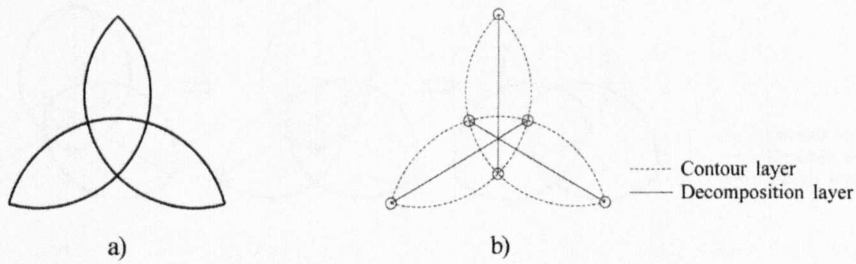


Figure 5.9. (a) initial concept design, (b) decomposition points and decomposition lines are placed in a different layer

Once decomposition points and decomposition lines are defined, they can be introduced in a shape rule. Figure 5.10 shows a rule, called *decomposition rule*, which adds a new outline between two decomposition points. The rule only represents a half petal because the intention is to produce designs with symmetrical petals, so the rule applies to only one half. Notice that the outline is placed in the design layer.

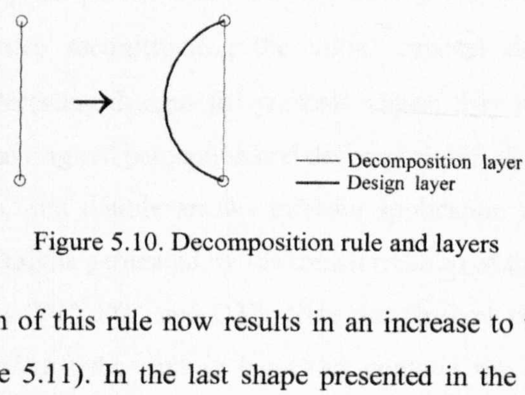


Figure 5.10. Decomposition rule and layers

The application of this rule now results in an increase to the concavity of all three petals (Figure 5.11). In the last shape presented in the sequence shown in Figure 5.11, the contour layer and decomposition layer have been turned off in order to clearly see the result. This example shows that decomposition points and decomposition lines are useful when exploring designs with overlapping elements through shape rules.

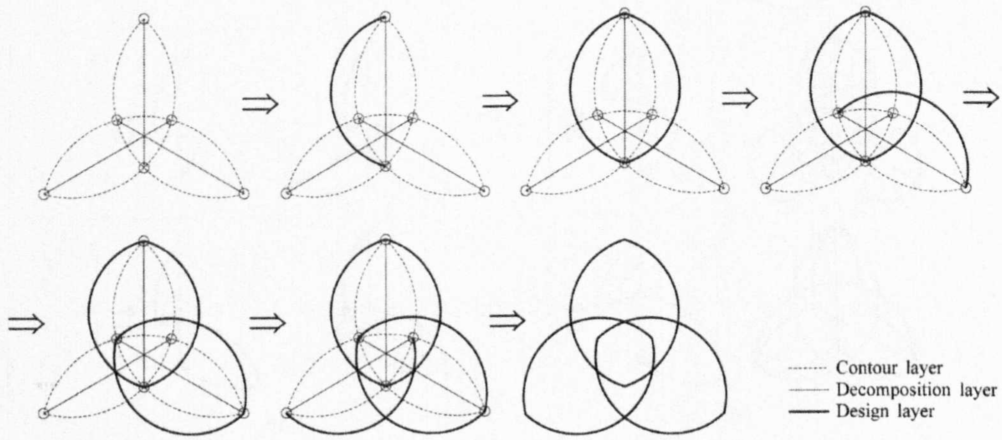


Figure 5.11. Successive application of the decomposition rule

Decomposition points and decomposition lines are placed to explicitly define the perceived decomposition of a shape. However, this is often not enough for shapes containing crossing decomposition lines. Figure 5.12a shows three different interpretations (as heavy arcs) of the same decomposition lines. Each interpretation is formalized with a shape decomposition rule (Dl, D2, and D3), which adds the perceived outline (thick line) to the decomposition line. The application of the decomposition rule Dl to the star-like diagram reconstructs the shape from elements making up the petals. Rules D2 and D3 are two more reinterpretations that, apart from also reconstructing the initial concept design, can produce unexpected and interesting designs in synthesis stages; they are unexpected from the standpoint of the original perception and decomposition. Single arrows are used to define the rules, and double arrows indicate application of the rules. Figure 5.12b shows new designs generated by the transformation of the outlines with new decomposition rules (Dl', D2', and D3'). Note that the new designs are placed in the design layer and that the contour layer that contains the initial design is not illustrated.

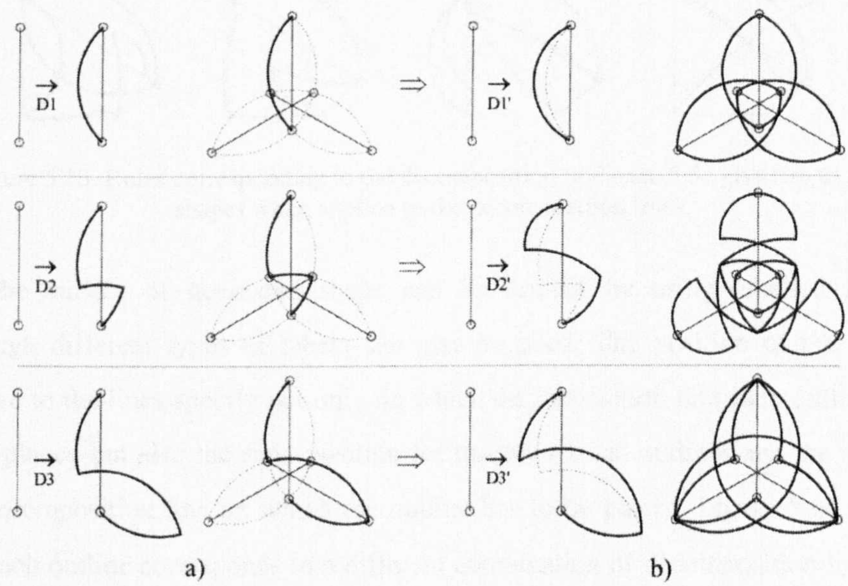


Figure 5.12. (a) Decomposition rules reconstruct the initial concept design from decomposition lines and (b) variations in the decomposition rules generate new designs

The interpretations are created from the decomposition lines by the application of decomposition rules. The simple example corresponding to the initial interpretation is shown in the top row in Figure 5.12 whereas more complex decomposition rules create the reinterpretations. Frequently, shapes in product design are more complex than these examples with several different elements being perceived in one shape. Elements are not always symmetrical or repeat across the shape. Corresponding decomposition rules might then add any element to any single decomposition line in such a way that a huge number of inappropriate combinations would emerge. Consider Figure 5.13, for example, where decomposition rules corresponding to the same diagram of elements presented in Figure 5.5c can generate widely differing designs. The associations between lines and curved elements expressed by the decomposition rules are all present in the initial interpretation. However, in these examples the decomposition lines are not distinguished from one another; thus, the rules used in different positions give rise to radically new shapes as the rules are applied.

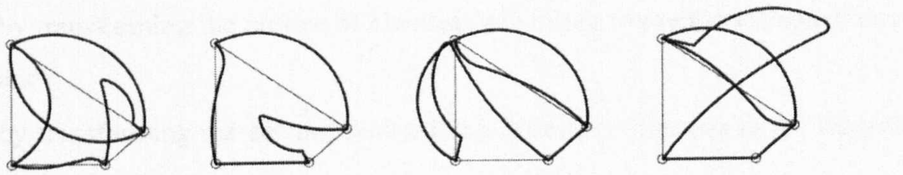
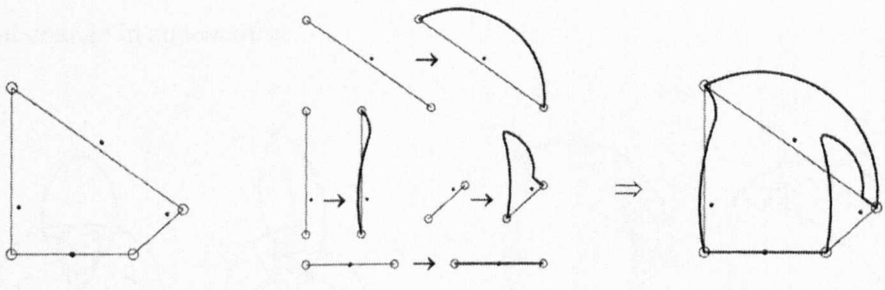


Figure 5.13. Rules corresponding to the decomposition in Figure 5.5c give rise to new shapes when applied to the decomposition lines

The variety of generated shape can be limited by using labelled points, although different types of labels can also be used. The position of the points relative to the lines specify not only on which decomposition line each outline has to be placed but also the right position for unsymmetrical outlines and the side of the decomposition line on which the outline has to be placed. Figure 5.14 shows that each outline corresponds to a different combination of decomposition line and point. Once labels are defined, the designer gets a duplication, which is the initial shape redrawn and ready to be explored. During the exploratory stage, the user may want to totally or partially ignore the labels with the purpose of increasing the number of design alternatives. We shall return to this in Chapter 7.



a) b) c)

Figure 5.14. (a) Diagram of elements, (b) set of labelled decomposition rules, (c) the labels allow the initial concept design to be uniquely reconstructed by the decomposition rules

5.3.2 Transformation of the defined elements

The main purpose for decomposing designs is to assist design exploration which is based on shape transformation. In the decomposition layer designs can be transformed in two different ways:

- by transforming the outline of elements according to predefined constraints; and
- by transforming the decomposition lines, leading to changes in the diagram of elements.

Any new design generated in these ways will be composed of the same elements. Hence, the new designs will possess consistency and display some sort of similarity, at least according to the designer's perception. Each gives more or less radical designs. For example, manipulating the outlines of elements in Figure 5.5a generates Figure 5.15a, whereas manipulating the decomposition lines generates Figure 5.15b. Both new designs illustrated in Figure 5.15a and b can still be decomposed into three petals, consistent with the perception of the initial concept design. Manipulating decomposition lines appears to lead to more radical designs. Figure 5.15c shows an example of exploring new jug kettles by manipulating the outline of the elements. The appearance of the object has been changed but strong similarities are still evident because the diagram of elements has not changed. Figure 5.15d provides a modification of decomposition lines leading to a more radical change in appearance.

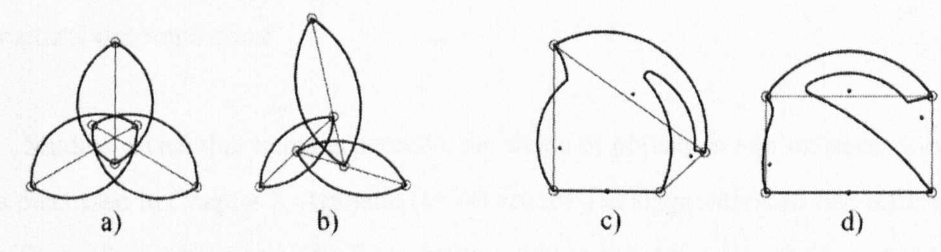


Figure 5.15. Modifying the relations among decomposition lines

5.4 Setting up structures

Once interpretations of an initial shape are formalised by decompositions and associated decomposition rules, the designer can explore the new design space by transforming the outline of elements and decomposition lines. Designers may group several elements and explore different spatial relations between groups in order to achieve a logical internal organization of the whole shape. This internal organization assists designers in designing complex compositions and gives coherence to ranges of designs of the same idea. The model presented here groups one or more elements through a structure defined by the designer, which is placed in the structure layer.

5.4.1 Definition of the structures

According to Earl (1997), the internal structure of a shape is associated with the perceived elements of a shape. In a manner similar to the shape descriptions of decomposition, structure is described by shapes of *structural lines*. Straight lines are a straightforward shape description of structure; but other structural shapes, such as circles and arcs, may be more effective representations as aids to exploration. Dotted thick lines are used to represent structural lines in order to differentiate them from decomposition lines. The key in Figure 5.16d shows the types of lines used to represent each layer. The structural lines shown in Figure 5.16b use decomposition points as end points whereas those in Figure 5.16c identify a particular bilateral symmetry. However, two questions arise. Does it make sense to define decomposition points that are then ignored in the structural decomposition? And, why should decomposition into elements differ from structural decomposition?

Studies reveal that humans perceive the shape of objects in two different ways. As discussed in Chapter 2, Arnheim (1974) argues that shape refers to two different qualities of visual objects. The first quality refers to the shape actually seen and the second quality is constructed cognitively. Similarly, Loran (1943), in describing Cézanne's compositions, argued that one might consider that there is a surface structure and a deep structure within an artwork. Surface structure corresponds to many of the observable properties, like lines and colours, whereas deep structure refers to how the artwork is organized. Similar categories were presented by

Birkhoff (1933) in establishing an aesthetic measure and Stiny and Gips (1978) in developing general computational models for criticism and design.

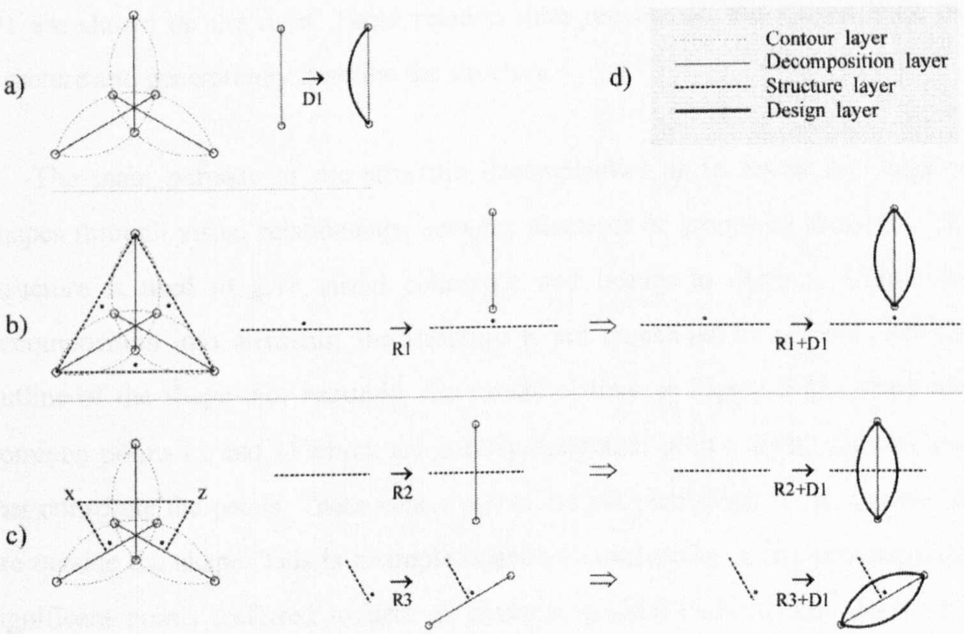


Figure 5.16. Structure layer shapes indicating: (b) full symmetry of the three petal shape, (c) bilateral symmetry. The relation rules express relations between the structure lines, decomposition lines and elements of the shape

Following this distinction, it is possible to distinguish the perception of the structure and elements of the same shape. Each one deals with different qualities at different levels of abstraction. Consider, for example, Figure 5.16b and c. On the left-hand side two similar shapes are decomposed into similar elements, but different structures are defined. That is, both shapes are perceived as a composition of three petals (see Figure 5.16a) but with different relations between them. The structure and its marks shown in Figure 5.16b suggest that the whole shape is seen as a petal rotated three times. Such a structure could be the shape of a fan. In contrast, the structure and marks in Figure 5.16c form a span across the shape, suggesting that the shape is seen as one individual petal and two more mirrored petals. Such a structure might suggest the shape of an arrow or rocket. The shape rules (R1, R2, and R3) are referred to here as *relation rules,* and they express the relations between structural lines and decomposition lines of the shape. In order to visualize the relation between the elements and structure, the decomposition rule is applied inside the relation rule. These composite rules R1 + D1, R2 + D1, and R3 + D1 are shown on the right. These relation rules reconstruct the shapes from the structure and generatively describe the structure.

The main purpose of the structure decomposition is to reveal and explore shapes through visual relationships between elements or groups of elements. The structure is used to give visual coherence and beauty to designs. Unlike the decomposition into elements, the structure is not embedded or aligned with the outline of the shape. For example, the structural lines in Figure 5.16c share two common points (x and z) which are exactly the center points of the circular arcs that constitute the petals. These center points are not embedded in the outline but are outside the shape. This is a simple cognitive construction using geometrically significant points (referred to here as *strategic points*) such as the center of a circular arc, but any points can be chosen according to intention. Although strategic points may also include perceived points of discontinuity, their identification depends more upon subjective criteria than perceptual 'laws'. Hence, the definition of strategic points is more flexible than points of discontinuity.

5.4.2 Transformation of the defined structure

In a similar way to decomposition into elements, the definition of the structure is subjective as well as dynamic: a designer defines a structure, explores, sees, describes a new structure, and so on. New designs can be explored in two different ways on the structure layer:

- by transforming spatial relations between a structural line and its related decomposition lines; and
- by transforming spatial relations between structural lines.

The illustrations in Figure 5.17c and e show exploration of the first type and Figure 5.17d and f show exploration of the second type for structures defined in Figure 5.16.

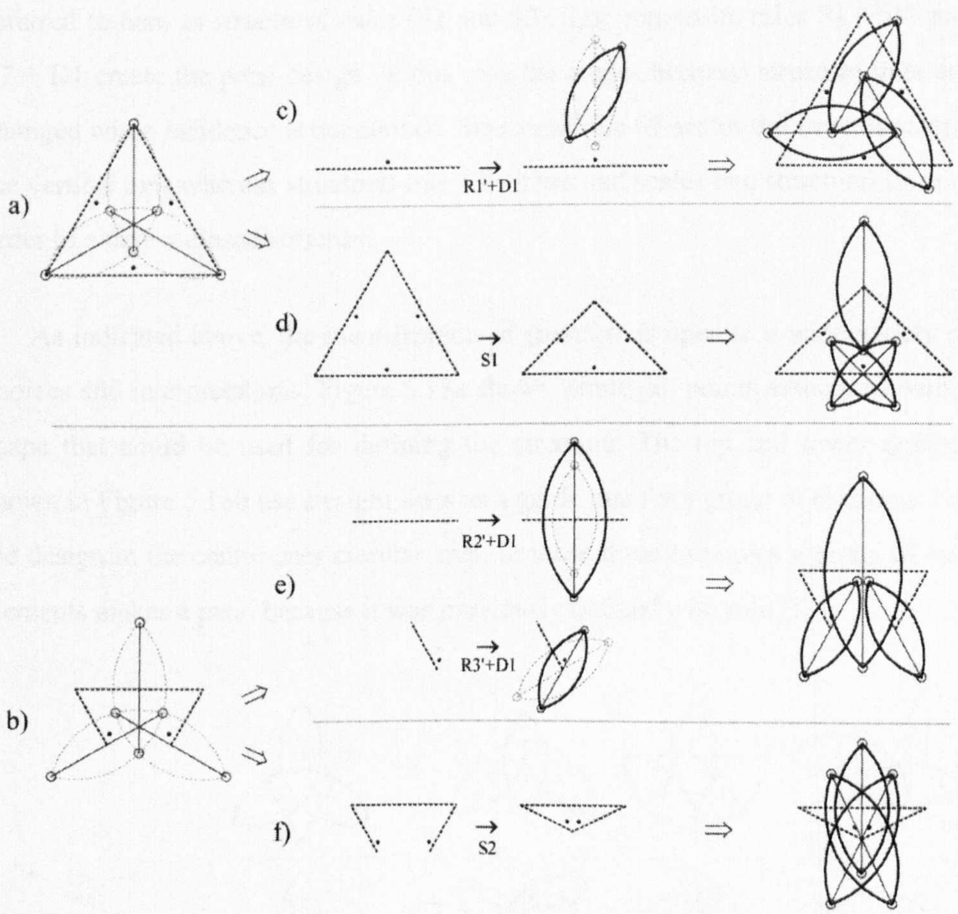


Figure 5.17. (a, b) Structures defined in Figure 5.16; (c, e) modifying the relations between structure and decomposition lines through relation rules R1', R2', and R3'; and (d, f) modifying relations between different structural lines through structure rules S1 and S2

Figure 5.17c and e show two designs created by manipulating the relation between structural lines (the surrounding triangle of dotted lines in Figure 5.17a or the 'span' in Figure 5.17b) and the decomposition lines (the three lines across the axes of the petals) through relation rules. In the relation rule R1' + D1 the decomposition line has been rotated from its center. In the rule R2' + D1 the decomposition line has been scaled, and in the rule R3' + D1 the decomposition line has been rotated and scaled. In a similar way to Figure 5.16, the relation rules in Figure 5.17c and e are composites of rules (R1', R2', and R3') that change relations between structure and decomposition lines and rules (D1, D2, and D3), which add the elements to the decomposition lines. Figure 5.17d and f show new designs created by manipulating the relations of structural lines through shape rules, referred to here as *structural rules* (S1 and S2). The composite rules S1 + D1 and S2 + D1 create the petal design. In this case the angles between structure lines are changed while incidence is maintained. Structural rule S1 scales the structure along the vertical axis whereas structural rule S2 rotates and scales two structural lines in order to obtain a closed structure.

As indicated above, the identification of structure is open to a wide variety of choices and interpretations. Figure 5.18a shows 'strategic' points associated with a shape that could be used for defining the structure. The top and lower designs shown in Figure 5.18b use straight lines as a guide line for a group of elements, but the design in the centre uses circular arcs. In these three examples a group of two elements makes a petal because it was previously defined with rule D1.

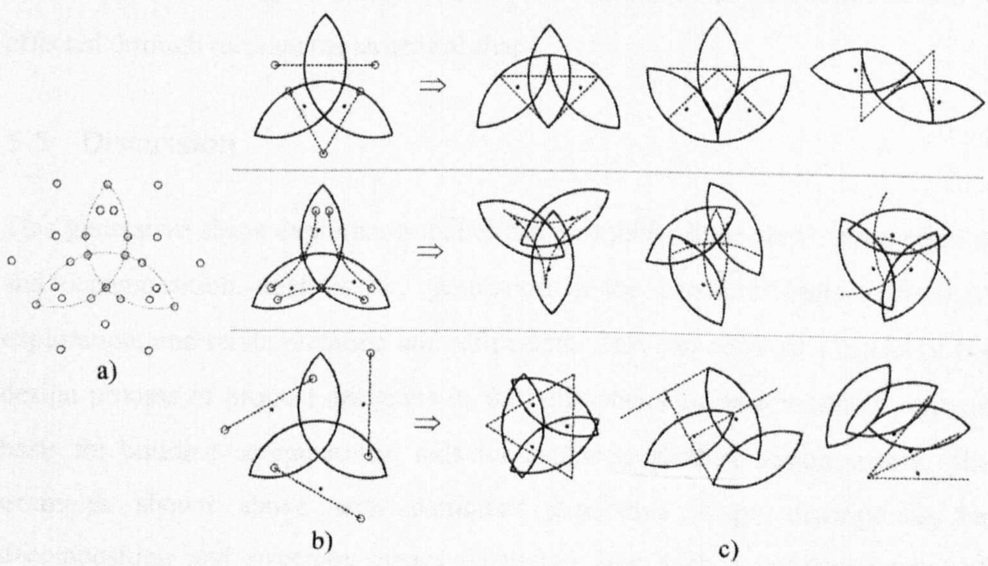


Figure 5.18. (a) Strategic points, (b) a definition of structure by selecting strategic points, and (c) reconfiguring the structure lines with associated changes to the shape

Once structure shapes are defined (three examples are given in Figure 5.18b, which show strategic points identified with circles), the structure can be manipulated in such a way that the resulting shapes follow 'perceptually interesting' patterns. Figure 5.18c illustrates several examples.

Introducing structure makes the design space larger. When the designer decomposes a shape into elements, the design space, at least in terms of shape, is actually being narrowed down through selection from unlimited potential decompositions. At that level the spatial position of each element is not considered. However, as soon as the structure is defined, more variables (the spatial relations among elements) are brought into play and the design space is potentially expanded again. Exploring changes to the structure shape (i.e. the structural lines) can result in a radical change of the design shape. When the designer is satisfied with a certain structure, the design space can be narrowed down again by fixing the structure and concentrating on manipulating the outline of elements. New sketches can be generated by manipulating fine details of an initial concept design, but if designers do not see any potential they can change the structure. This is achieved by adding, subtracting, or changing the spatial relations between elements and is effected through rules on the structural shape.

5.5 Discussion

This generative shape exploration model has essentially three steps: interpretation and decomposition, analysis and generation in the structure shape to broaden exploration, and reinterpretation and refinement. This can serve as a model of the design process of product designers in the early stages of design, which forms a basis for building computational aids for exploring product design spaces. The examples shown above with particular generative shape descriptions for decomposition and structure shapes illustrated how such a computational tool works.

As shown in Figure 5.18, the structure shape can be manipulated by hand without constraint on possible changes. However, more systematic exploration of new structures can be achieved through well-defined rules in a computational implementation. Two simple examples are illustrated to summarize the explorations examined in this chapter. Figure 5.19 provides an example of exploring new structures of a shape perceptually composed of two groups of elements, R1 + D1 and R2 + D2. Each group of elements is represented by a structural line 'strategically' positioned according to the intentions of the designer. Here, the rules define possible spatial relations between two structural lines. In this example, the structural rule S1 adds one structural line to another line found at 90°, resulting in a T-shape. Structural rule S2 adds one structural line to another line found at 90°, resulting in an X-shape.

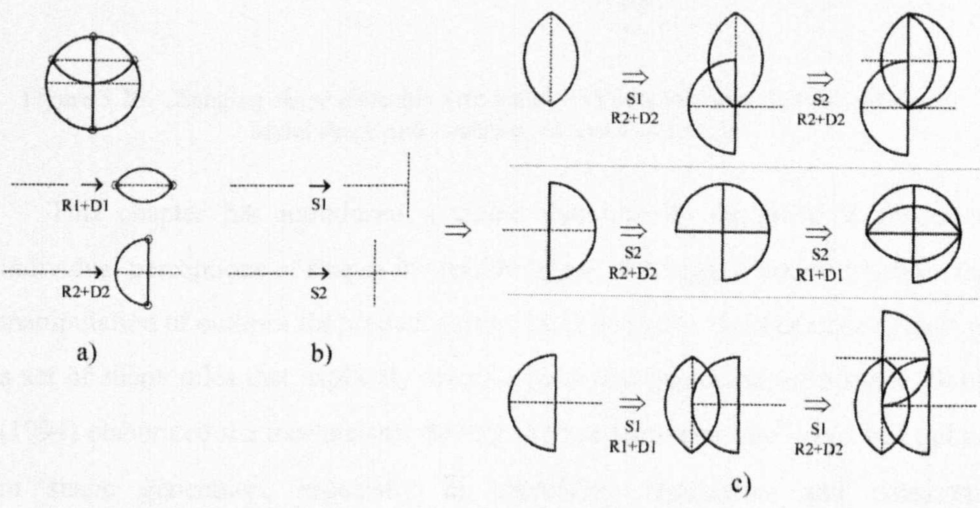


Figure 5.19. (a) Initial concept design, (b) two structural rules, and (c) shapes generated by rules that create new structure shapes

While exploring new structures, a new decomposition into elements can be included that corresponds to a new interpretation. Figure 5.19a shows the same initial shape interpreted in two different ways. The curve segment elements are different but grouped similarly in the structures. Structure rules S1 and S2 are applied with each of the decompositions R1 + D1 and R2 + D2.

Another example of this wide ranging exploration is shown in Figure 5.20 with the same initial shape and structure rules as in Figure 5.19 but with different decomposition points, lines, and rules (D3, D4, and D5) as well as different relations rules R3 and R4 between the decomposition lines and structure lines.

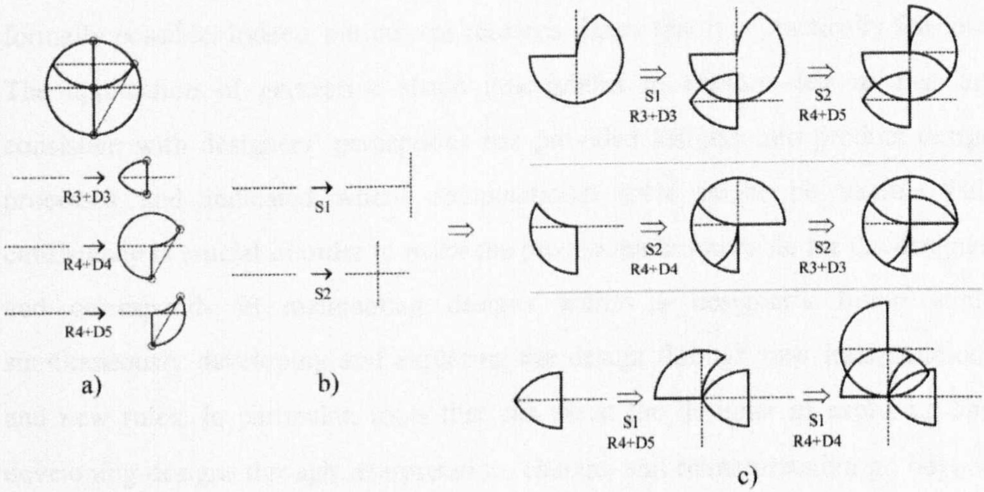


Figure 5.20. Changing shape elements associated with structure lines but using the same initial shape and structure rules as Figure 5.19

This chapter has introduced a model that enables designers to formalize individual perceptions of shapes in creative stages of design. It concentrates on the manipulation of outlines for product design. Here, the term 'formalization' refers to a set of shape rules that explicitly reveal a particular perception of a shape. Stiny (1994) elaborated the mechanisms through which decomposition could be applied in shape generation, especially in identifying continuous and consistent interpretations created through rules. Each decomposition that describes the shape can correspond to a different perception.

The perception of a shape can vary from person to person. Often, the reinterpretation of shapes plays an important role in creative activities. Designers constantly change their interpretations during the exploration process in order to produce creative designs. The aim of this chapter has been to provide a model to be able to describe how designers identify their individual perception of a shape at any stage in design. Further, the model shows how the consequences of particular perceptions can be explored through generative shape mechanisms and suggests areas where computer support in generating creative designs would be applicable. By concentrating on the exploration of product design shape, through using shape rules, embedding this exploratory model of design in a computational tool is formally possible. Indeed, our current research shows that it is practically feasible. The application of generative shape descriptions to explore designs that are consistent with designers' perceptions has provided insights into product design processes and indicated where computational tools might be useful. This consistency is crucial in order to make the process understandable for the designer and corresponds to maintaining designs within a designer's frame while simultaneously developing and exploring the design through new interpretations and new rules. In particular, tools that can assist the designer in exploring and developing designs through interpretation, change, and reinterpretation go beyond the analytical approaches to one that is synthetic and exploratory (Stiny 2006). The tentative suggestions in this chapter go some way towards this goal. Our current research in the rules and methods for the exploration of the curved shapes in the four descriptions (contour, decomposition, structure, and design) uses a variety of generative shape descriptions for curves (Jowers et al. 2004; Prats et al. 2004).

This programme of using generative shape descriptions to explore and develop new designs can be considered as an iteration of shape analysis and synthesis that is repeated on a small and large scale through a product design process. The preparatory stages of interpretation, decomposition, change, and reinterpretation explore perception and inspiration. They set down the framework for shape generation of new designs as new insights and interpretations occur. The whole process is iterative. The design processes modeled in this chapter are essentially exploratory, not being governed by preconceived rules, but are free to create rules to follow inspiration, perception, and interpretation. More detailed exploration of outline and shape can be undertaken in a similar but geometrically more detailed way through shape rules applied to the elements in a product outline.

Recall that one driver for this research on design exploration was the examination of sequences of exploratory sketches (as it is illustrated in Chapter 3) produced by industrial designers. These were created in response to a particular task to explore the outlines of jug kettle designs. The explorations undertaken by the industrial designers can be mirrored by the more formal explorations in decomposition and structure. Further stages in this exploration include progressive refinement of design families. Shape rules modify elements in the product outlines to create product families of related designs. These families can be selectively refined. A specific design is selected from a family and variations are generated with fewer and fewer obvious differences. We shall return to the idea of design families in Chapter 7.

The early stages of product design are characterized by extensive explorations of possibilities. Generative shape descriptions offer a route to formalizing some of the activities in this exploration. In particular, this chapter proposes a tentative model in which four shape descriptions of contour, decomposition, structure, and design are developed side by side. Some of the generative shape rules apply across two or more of these descriptions, so that changes across descriptions are related. Further, rules apply to change the spatial relations between shape elements across two or more descriptions. Designs expressed by contour, decomposition, and structure descriptions offer starting points for exploration though changing the spatial relations between the different descriptions. This exploration presents designs consistent with the individual descriptions and structure.

These consistent stylistic changes provide the basis for assisting designers to explore the consequences of their interpretations and structural views without being prescriptive. This chapter provided examples of the different descriptions and their implementations in terms of rules. The proposals for assisting designers outlined here are continued through the systematic generation of design families. Generative shape descriptions mean that radically new interpretations can be developed at any point. On the one hand, generative shape descriptions analyze and explain; on the other hand, they synthesize and explore. The process of creative design in this chapter encompasses both explanation and exploration.

Chapter 6

Establishing rules for design exploration

Overview

This chapter contains details of the decomposition rules presented in Chapter 5. It shows how the outlines of designs depicted in sketches can be explicitly described and transformed via decomposition rules. For the sake of this research, a new system for describing and transforming outlines using a small set of parameters has been devised. In addition, two significant features, added to the decomposition rules, are presented which will assist designers in explicitly describing aspects of design requirements. One feature assists defining connections between outlines. The other feature provides decomposition rules with flexibility and control over the process of transforming outlines, particularly outlines composed of curved lines.

6.1 Introduction

Designers frequently explore designs by generating and transforming shapes through pictorial representations – sketches in particular. Chapter 5 has presented various types of shape rules that assist in defining and transforming two different properties of shapes: the outline and the structure. It has been shown that it is possible to transform the outline of a shape while maintaining its structure, and also transform the structure of a shape while maintaining the outlines of its elements. Although these two properties – outline and structure – can be tackled individually, during design exploration designers normally deal with both simultaneously. As a consequence, sequences of exploratory sketches may exhibit several transformations of outline and structure from one sketch to another. This suggests that some shape transformations occur in the designer's head but they are not subsequently graphically represented.

In generating designs via shape rules, however, each transformation applied to a shape is described explicitly. Hence, shape rules provide a plausible means for describing the exploration process by capturing – or imitating – designers' moves. But more importantly, shape rules generate novel designs according to personal requirements that could stimulate designers' creativity. Although shape grammars offer a remarkable potential for capturing designers' moves and generating creative designs, most shape grammar implementations, such as the Palladian grammar (Stiny and Mitchell 1978) and the Buick grammar (McCormack et al. 2004), employ shape rules for the purpose of analysis of particular styles and brands only. A few shape grammars, such as the Kindergarten grammar (Stiny 1980b), have been proposed for the purpose of design exploration – in the sense that the grammar can be easily redefined as new design requirements emerge during the design process. However, these approaches are limited to designs composed of basic shapes like blocks and do not support shapes like blobs. In addition, they focus on the transformation of the spatial position of the elements – that is to say, they focus on the structure of design instead of exploring variations on the outlines.

Generally, exploring designs for consumer products involves the generation of complex shapes, normally composed of curved lines. A number of shape grammars have been developed with the purpose of analysis of classes of consumer products. The shape rules used in these grammars normally support the transformation of curved lines which are described in terms of a set of parameters. However, information about how designers interact with these parameters via shape rules has not been provided. Such interaction with parameters, as well as the definition of the parameters, is crucial in design exploration. Not only because this facilitates the process of exploring designs in a systematic way, but also because this allows designers to explicitly classify types of curves according to their requirements.

This chapter focuses on how outlines can be defined and systematically transformed via shape rules. A system is proposed for describing curved lines with meaningful parameters which assist in defining types of curves in an explicit manner according to personal criteria. Such parametric curves are contained in the decomposition rules presented in Chapter 5. Thus, parameters provide a means for generating ranges of designs that exhibit similar characteristics, at least for the person who defines the rules. By transforming the outlines of depicted designs it is possible that the structure of the design also experiences some kind of transformation. This chapter gives details on how the outlines in decomposition rules can be associated with the structure of the design, in such a way that transformations in the outline can result in changes in the structure.

6.2 Parametric rules for design exploration

Parametric shape rules provide a useful means for both explaining and exploring designs. On the one hand, limiting ranges of values in parameters reveals the acceptable variability in shape feature. On the other hand, widening the range of values in a parameter generates new designs that may not have been possible earlier. But parametric rules can do more. They generalize the applicability of shape rules. In other words, a parametric shape rule can provide flexibility of application since it can be applied to a variety of shapes, and also transform that shape in a variety of ways (Figure 4.15 in Chapter 4 shows an example). Parametric shape rules are beneficial for rule-based systems that are intended to explore designs. As discussed in Chapter 4, there are three types of parametric rules based on which side of the rule is parameterized. The parameters can be defined (i) on the left-hand side of the rule, (ii) on both sides of the rule, or (iii) on the right-hand side of the rule. Consider the first type, where the parameters are defined in the left-hand side of the rule.

$$g(A) \rightarrow B$$

The variable g denotes that the shape A is parameterized, which means that this shape represents a set of shapes instead of a particular shape. This type of rule is applicable even if the design does not contain any shape that coincides with shape A but is within the range of values defined in g. As illustrated in section 4.5 in Chapter 4, a square defined in a parametric rule does not only transform squares but can also transform rectangles, and even quadrilaterals depending on how general or specific the parameters are. This type of parametric shape rule can normally be applied in many places in a design – most of them unexpected places – which makes the generative process difficult to control. This lack of control could be regulated by ordering parametric relations into a hierarchy as proposed by McCormack and Cagan (2002). This type of parametric rule may be useful when exploring a particular transformation in a variety of places in the design, but does not support the application of a variety of transformations to a particular place. Consider now the second type of parametric shape rule, where the parameters are defined on both sides of the rule.

$$g(A) \rightarrow g(B)$$

This type of parametric shape rule provides flexibility on both sides of the rule. In some particular cases (e.g. when generating random designs), this type of parametric rule can be very powerful in the sense that it can be applied in many places in the design and allows for many transformations. However, it is sometimes difficult to control the exploration process when using this type of rule. Consider the last type of parametric shape rule, where the parameters are defined in the right-hand side of the rule.

$$A \rightarrow g(B)$$

Using this type of parametric rule, one needs to specify the exact shape in the design that has to be replaced by the rule, but there is no need to specify the added shape, B, in an explicit way. Similar to the process of free-hand sketching, designers decide where to place the pencil before manipulating a sketch as well as the direction that the pencil moves. But the path between the start and end points of a stroke is often uncertain since in the early stages of design, strokes tend to be quick and imprecise. This type of rule offers more control of the exploration process than the first and second types of parametric rule.

This chapter focuses on the last type of rule, where only the right-hand shape of the rule is parameterized. This type has been used in previous shape grammar implementations, though not with the purpose of exploring designs but for explaining particular brands. The coffee maker grammar (Agarwal and Cagan 1998) and Buick grammar (McCormack et al. 2004) provide some examples of generating designs via this type of parametric rule. The next section introduces a simple method for representing designs composed of straight lines and curved lines in an explicit way. Using this method a vast range of outlines can be generated within the space of possibilities defined in the parameter.

6.3 Describing outlines via piecewise line-rules

Hogarth (1753) suggested that the essence of beauty in nature as well as man-made objects is rarely delivered by the simple geometry of a straight line or a circle, but by waving lines, or 'S' lines, that vary smoothly from one gradient to another. The outlines of most consumer products such as kettles, steam irons, and wine glasses exhibit different combinations of 'S' lines and curves with different curvatures. While straight lines only differ in their lengths and position in the space, curved lines differ in many aspects and some of these are difficult to describe explicitly – especially free-form curves. Most CAD systems, for example, describe curves through parametric polynomial representations such as Bézier and B-Splines. These polynomial representations provide a flexible way to generate and manipulate free-form curves. However, they do not provide a means for classifying types of curves according to their geometrical characteristics.

Unlike geometric shapes such as rectangles, triangles, and circles, which can be grouped into categories, each free-form curve is unique. A rectangle can be described as a four-sided plane with four right angles. Such a description encompasses all possible rectangles with different proportions including the square, and all of them are part of a broader category, namely quadrilaterals. These types of categories are very difficult to define for free-form shapes.

Consider the free-form curve shown in Figure 6.1. This curved line can be transformed in an infinite number of different ways, and transformations lead to new curved lines that are more or less similar to the original one. However, it might be difficult to tell which are the similarities and differences. This difficulty occurs because there is not a system available to easily describe free-form curves

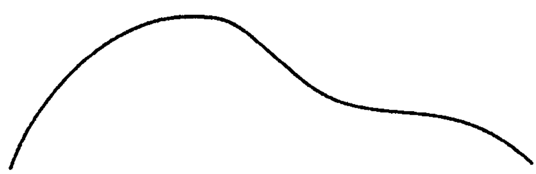


Figure 6.1. A free-form curve

One way of representing such a free-form curve is by approximating the shape with circular arcs (Figure 6.2). The advantage of using arcs is that they can be described with few parameters. For example, a circular arc can be described by its radius and the angle between the start and end of the arc. Some aesthetic properties might be lost after approximating free-form curves with circular arcs. However, in general designers do not deal with smooth and precise curved lines during the conceptual design stage. Approximations by circular arcs may not only provide sufficient precision for exploring designs at the early stages, but also a means for manipulating curved lines in a controllable and understandable way. This figure shows that decomposing a shape into circular arcs provides a means for describing approximations of free-form shapes explicitly. Manipulations of this line can now be reported in an understandable way. A myriad number of transformations of the line in Figure 6.2 can be generated by altering the values of the radius r and angle α of each arc.

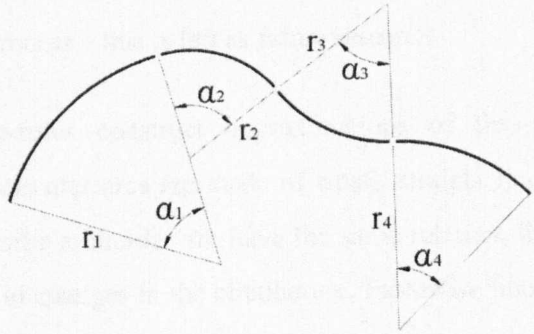


Figure 6.2. Approximation of the free-form curve with circular arcs.

The concept of decomposing shapes into line and circular arcs segments is not new, and has been applied in different methods and with different purposes. For example, 'chain codes' (Freeman 1974) describe the contour of objects by sequences of unit-size line segments with a given orientation. The output of the chain code is a sequence of numbers that express the direction of each line segment by using a four or eight directional encoding scheme. For instance, 000666444222 describes a square that consists of four sides composed of three-line segment. They are used for several purposes including data compression and shape recognition.

For the sake of this research, a method for representing free-form shapes based on the concept of chain codes has been devised. This method has two main purposes; (i) to encode characteristics of curved lines in a comprehensible way, and (ii) to generate sets of curved lines with similar characteristics. Such a method allows the transformation of curves explicitly by giving values to a set of parameters. These values are defined via shape rules, here referred to as *piecewise line-rules*. Unlike parametric polynomial curves (e.g. Bézier and B-Splines) the method presented here offers a valuable simplification when comparing geometrical characteristics of a set of curved lines. The simplicity of this method derives from its use of a few parameters to describe approximations of free-form curves. Obviously, piecewise line-rules do not offer the precision that parametric polynomial curves provide; therefore, it may be sometimes necessary to convert piecewise line-curves to conventional parametric curves, especially in later stages of the generation process – this is left as future research.

Piecewise line-rules construct approximations of free-form curves from circular arcs. The circular arcs are made of small, straight line segments. All the segments that describe a circular arc have the same relation, therefore changes of this relation result in changes in the circular arc. Piecewise line-rules are generally defined by three parameters:

- ß: the angle between lines segments
- R: the number of line segments
- Pd: the point of discontinuity

The piecewise line-rule, shown in top Figure 6.3, connects two (empty) points with a group of unit-size line segments making an approximation of a circular arc. The parameter ß defines the angle between line segments and the parameter R the number of line segments; in Figure 6.3, the value of R is 4. To increase the curvature of the circular arc a higher difference between the value of ß and 0 is required, whereas values closer to 0 will result in a reduction of the curvature, or a straight line if the value of ß is 0. The cross in the point is not part of the rule but it is used to indicate the direction in which the rule is applied; in this example the line segments are constructed from left to right. This means that this rule can be applied in four different ways; two possibilities from left to right – concave and convex – and two more possibilities from right to left – concave and convex. This can be constrained by using labels, which will be discussed later in this chapter.

To generate more complex curves it is necessary to introduce more groups of line segments in the rule. This is shown in the piecewise line-rule in the lower illustration in Figure 6.3. The second group of line segments follows on immediately from the first one and new parameters are introduced; ß, R, and Pd.

The parameter Pd defines the angle between two groups of line segments which creates a tangential discontinuity between them.

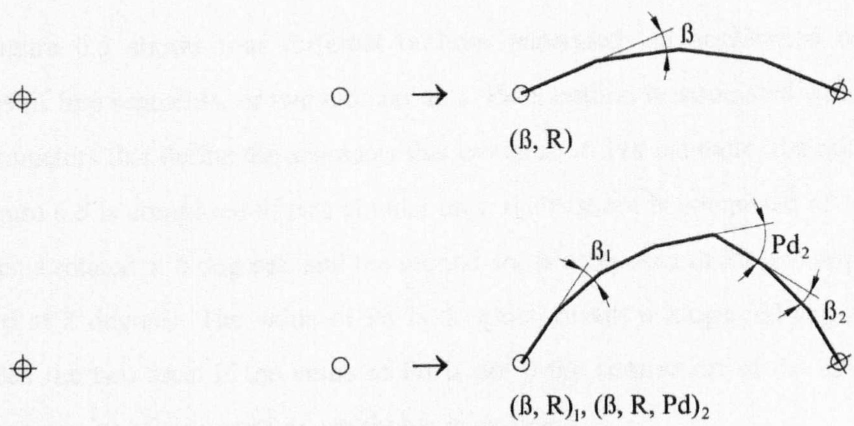


Figure 6.3. Piecewise line-rule and its parameters

In order to produce a tangential connection between two circular arcs, the value of Pd must be 0. Figure 6.4 shows an example of two circular arcs where the value of Pd is 0. Note that in order to produce a perfect tangent connection it is sometimes necessary to rotate the second circular arc to correct an error. This is done by the angle ε that is added to Pd if its value is 0, that is, if the connection between two arcs is tangential.

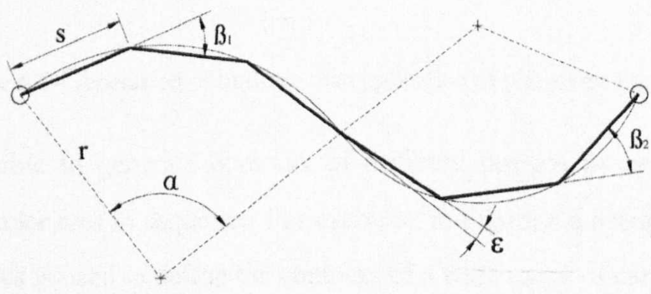


Figure 6.4. Radius and angle of the circular arc obtained from one piecewise line-rule's parameters

The parameters of circular arcs – radius and angle – are needed to identify this error. They can be obtained from the parameters used in the piecewise line-rule. The angle of the circular arc, α (shown in Figure 6.4) can be obtained through the following operation: α = ß x R. And the radius of the circular arc, r, can be obtained through: r = (s/2) / (sin (ß/2)); s being the length of the line segment.

Figure 6.5 shows four different outlines generated via application of two groups of line segments, or two circular arcs. Each outline is associated with a list of parameters that define the segments that compose it. For example, the outline 1 in Figure 6.5 is composed of two circular arcs; the first arc is composed of 10 line segments rotated at 6 degrees, and the second arc is composed of 20 line segments rotated at 2 degrees. The value of Pd is 0, which makes a tangential connection between the two arcs. If the value of Pd is not 0 the connection of the arcs will produce a point of discontinuity, as shown in outline 4.

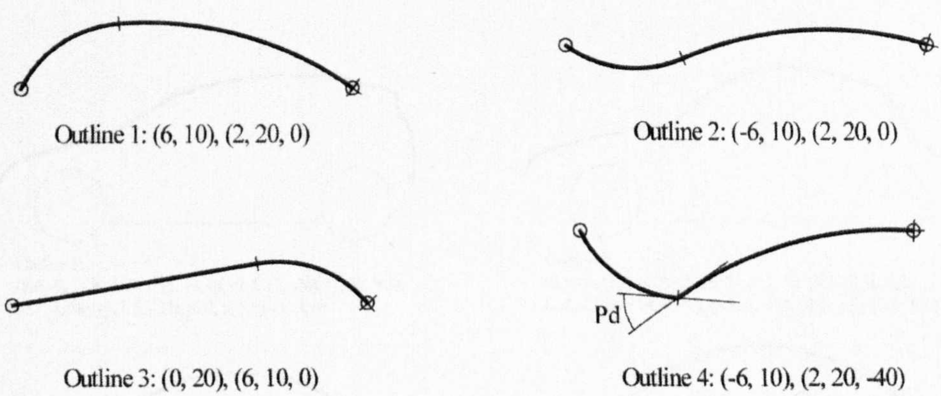
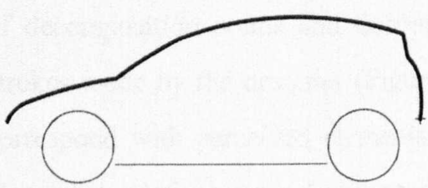


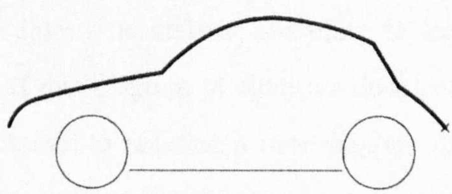
Figure 6.5. Generation of outlines via application of piecewise line-rules

It is possible to generate contours of different designs by application of a variety of circular arcs in sequence. For example, in Figure 6.6 a sequence of up to ten circular arcs is used to define the contours of a wide range of cars. Note that an additional rule, not illustrated here, is used to add the wheels. The code of the outlines provides a means for generating outlines that share some similarities. For example, the outlines in Figure 6.6 are consistent in that they include a considerable point of discontinuity just after the third circular arc, which differentiates the hood from the windscreen of the car. The code is used to communicate to the computer a set of design intentions required to perform a particular design, but not to be used directly by the designer.

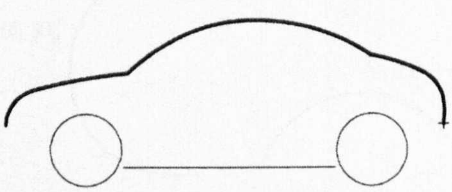
Designers can use different drawing techniques to explore their ideas when sketching with pencil and paper. In general, they produce a continuous line stroke from one point to another to depict a piece of the outline of a design. Similarly the piecewise line-rules can generate an infinite variety of paths between two points. Piecewise line-rules can generate different outlines with similar features. This section has presented a method that allows manipulating pieces of curves intuitively by changing the values of meaningful parameters. Repetitive changes of the values of parameters results in a variety of different outlines that share similar features, at least for the designer.



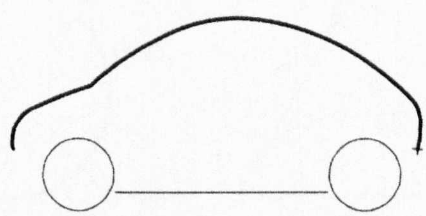
Outline 1:
(8.6, 4), (1.8, 2, 0), (0.6, 14, 0), (0.3, 12, -24), (1, 39, 9.3), (0.7, 4, 58), (5.7, 5, -27), (0.2, 5, 5.8), (4, 3, 0)



Outline 2:
(8.9, 6), (1.4, 6, 0), (0, 19, 0), (1.7, 12, -37), (2, 8, 5.2), (1.4, 22, 0), (0.4, 9, 27), (1.3, 6, -26), (0, 2, 3.2), (2.3, 3, 0)



Outline 3:
(7, 4), (8.6, 4, 0), (0.3, 15, 0), (0.8, 11, -29), (1.8, 5, 5.4), (1.6, 27, 0), (4, 3, -27), (1, 6, 0), (9.3, 5, 0), (4.6, 6, 0)



Outline 4:
(8.4, 7), (6.6, 2, 0), (0.6, 11, 0), (0.8, 19, -21), (1.5, 14, 3.7), (1.3, 19, 0), (1, 6, 0), (0.4, 7, 0), (9.8, 4, 0), (2.9, 7, 0)

Figure 6.6. Car profiles generated via piecewise line-rules

6.4 Transforming designs via piecewise line-rules

Figure 6.7a, b, and c illustrate a possible sequence of strokes to construct a triquetra composed of three arcs. After the production of each arc, the parameters (ß, R) are obtained by approximating the arc with piecewise line segments and a piecewise line-rule similar to Figure 6.3 is defined. As has been shown in Figure

6.5 and Figure 6.6 it is possible that outlines may be composed of more than one arc. In such cases, the parameters obtained are $(ß, R)_1$, $(ß, R, Pd)_2$, …, $(ß, R, Pd)_n$, n being the number of circular arcs needed to approximate the outline. Obtaining the parameters (ß, R, Pd) from circular arcs is not difficult. The mathematical relation between piecewise parameters and circular arcs has been shown in the previous section. However, circular arc approximation of strokes represented, for example, as B-splines is more complex. Several works on curve fitting using arcs have been reported, especially those using *biarcs* that are piecewise circular arcs which are connected together to allow for tangent continuity (Bolton 1975; Ong et al. 1996). Nonetheless, a detailed examination of such technical issues is not within the scope of this thesis and must be left for further research.

Once the piecewise parameters are obtained, the diagram of elements – made of decomposition points and decomposition lines – is defined according to the strokes made by the designer (Figure 6.7d). If this diagram of elements does not correspond with perceived elements it is possible to redefine a new diagram of elements by defining new decomposition points and/or decomposition lines.

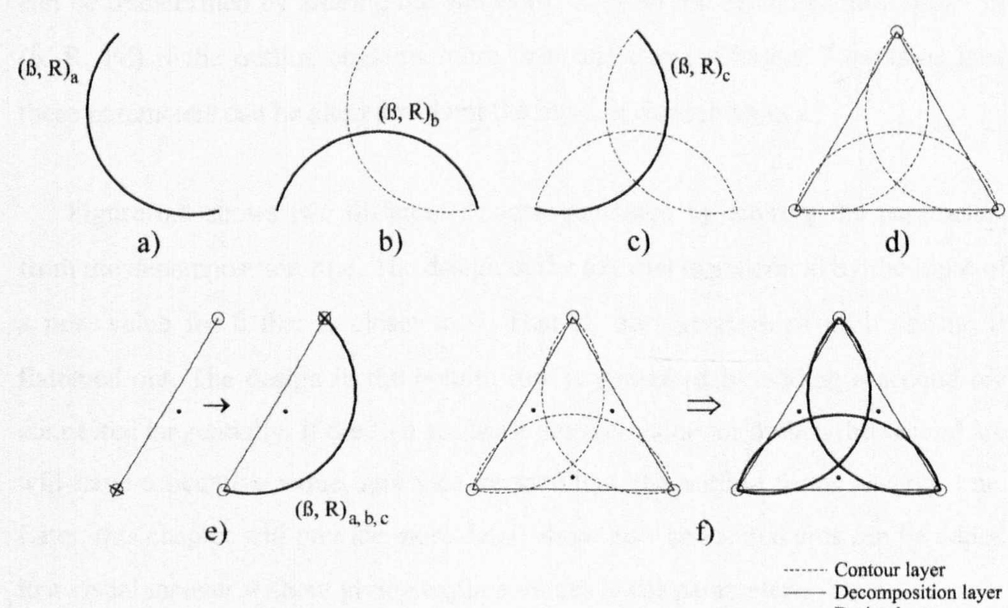


Figure 6.7. (a-d)Definition of decomposition points and decomposition lines in relation to the strokes, (e and f) the decomposition rule redraws the triquetra

Following the example in Figure 6.7, only one decomposition rule is necessary to describe the triquetra, as all three arcs – $(\beta, R)_a$, $(\beta, R)_b$, and $(\beta, R)_c$ – have similar values (Figure 6.7e). Once the decomposition rule is defined, the designer may want to add some labels (e.g. points) to the rule and diagram of elements in order to constrain the applicability of the rule. Figure 6.7f shows how the application of the rule to the diagram of elements redraws the triquetra in a different layer – design layer. Recall that single arrows are used to define the rules and double arrows indicate application of the rules.

The decomposition rule is defined as shown in Figure 6.7e. The left-hand side of the rule contains two (empty) points which will be connected with an outline defined by piecewise line segments as shown in the right-hand side of the rule. Chapter 5 has discussed two different levels of abstraction concerning shape transformation; one level deals with the outline of the design and the other with the structure. In general, decomposition rules are used to modify outlines but, as will be discussed in the next section, these rules can also modify the structure. For now, however, let us consider only outline transformation. The outline of the triquetra can be transformed by altering the values (β, R) from the decomposition rule – or (β, R, Pd) if the outline contains more than one curve. Chapter 7 explains how these parameters can be altered without the input of explicit values.

Figure 6.8 shows two different designs generated by altering the parameters from the decomposition rule. The design in the top row is generated by the input of a new value for β that is closer to 0. That is, the curvature of each outline is flattened out. The design in the bottom row is generated by adding a second arc connected tangentially. If the first arc has a positive value for β, then the second arc will have a negative value, and vice versa. Thus, the outline forms a wavy line. Later, this chapter will provide more detail about how connected arcs can be added in a visual manner without giving explicit values to the parameters.

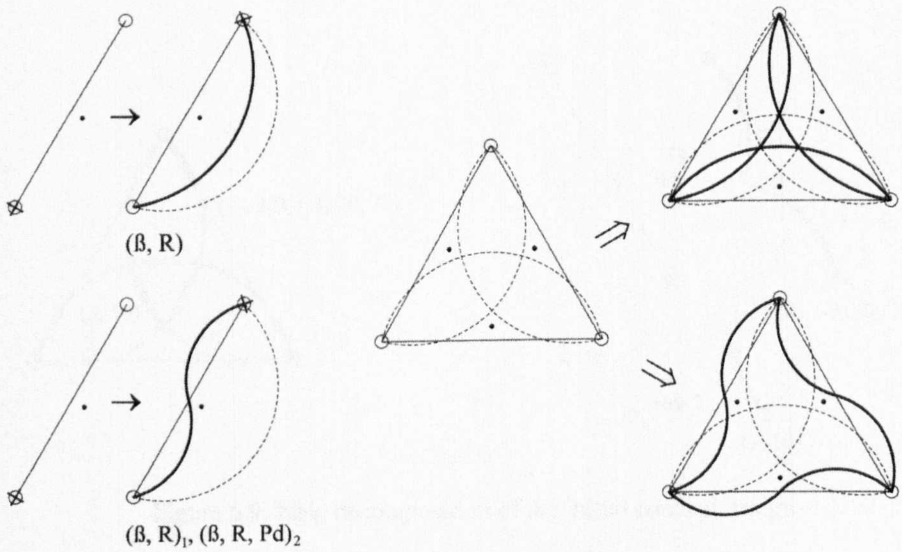


Figure 6.8. Changing the values of the parameters

6.4.1 Establishing connections between dependant elements

In many instances, when a designer modifies a sketch, changes in the outline of one element – similar to Figure 6.8 – may also involve changes in other associated elements. For example, the outline that defines the shape of a kettle could be decomposed into several different elements including body and spout. Generally, the spout of a kettle is attached to its body; therefore the position of the element 'spout' is associated with the outline of the element 'body'. As a consequence, modifications in the outline that represents the body may change the spatial position of the spout. In addition, variations in elements that are associated with other elements may also cause significant changes in the structure of the design. This section gives details about basic features that could be added to decomposition rules in order to deal with associated elements.

Consider that the triquetra in Figure 6.7 is interpreted differently and decomposed as shown in Figure 6.9. Now the diagram of elements contains two triangles that decompose the design into six elements. Three of them are made of two circular arcs connected in such a way that produces a point of discontinuity – rule 1 – and the other three elements are made of one single circular arc – rule 2.

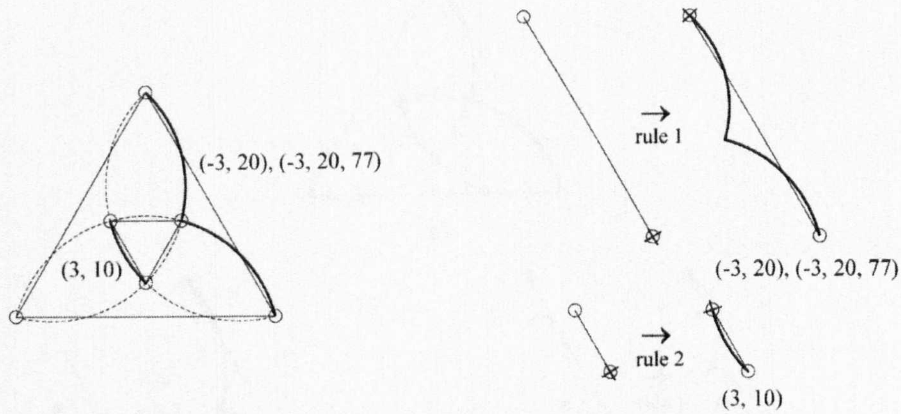


Figure 6.9. New decomposition of the initial concept design

As in Figure 6.8, new designs can be generated by modifying the values of the parameters. Observe that the point of discontinuity in the outline defined in rule 1 corresponds with one decomposition point defined in rule 2. Suppose that this is a condition to be preserved during the generative process. In other words, the decomposition points placed on the limits of the short outlines – defined in rule 2 – will move if the points of discontinuity of the long outlines – defined in rule 1 – move. The relation between outlines is here described with *mobile decomposition points*. These types of decomposition points are marked with a point in the centre of the decomposition point as shown in Figure 6.10a and b. Observe that a mobile decomposition point is placed in rule 1. In Figure 6.10c the values of the parameters have been modified, which move the initial position of the point of discontinuity.

The application of the modified rule 1' to the diagram of elements misplaces the mobile decomposition points. As a consequence, the short decomposition lines are left without decomposition points, and rule 2' cannot be applied because the left-hand side shape of the rule cannot be found embedded in the design. This occurs because the decomposition line does not move as decomposition points do. The connection between them can be described through a parametric rule that reconnects uncompleted decomposition lines (Figure 6.11).

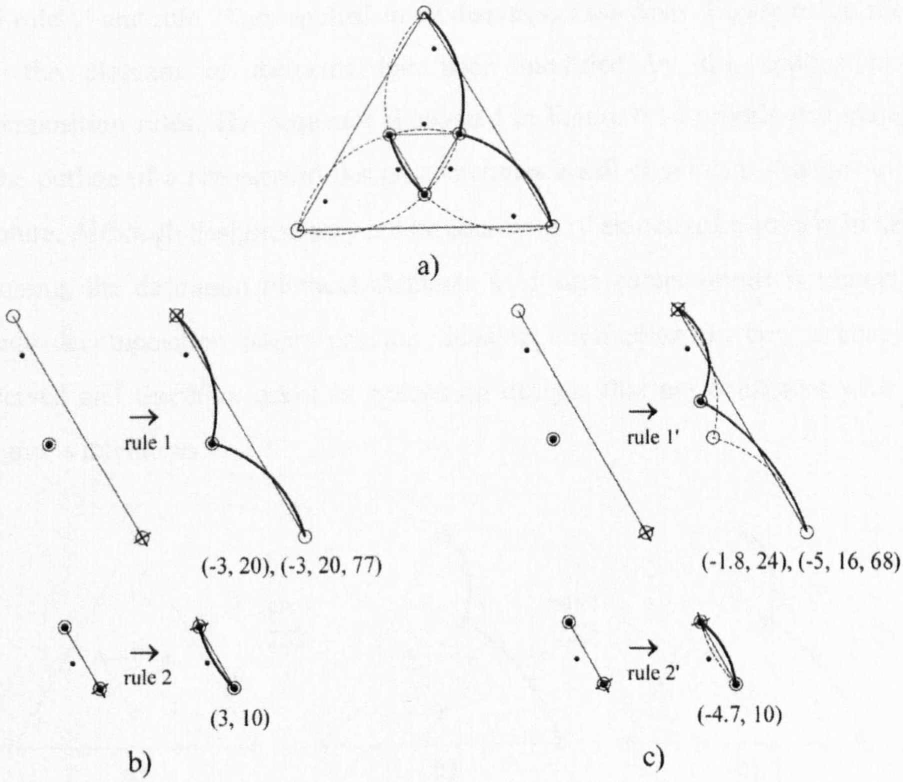


Figure 6.10. (a and b) Introduction of labels and mobile decomposition points to diagram of elements and rules, (c) variations in the values of the parameters

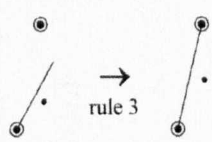


Figure 6.11. Reconnection of decomposition lines with decomposition points

The successive application of rule 1', rule 2', and rule 3 to the diagram of elements generates the design in Figure 6.12g. Note that the elements introduced previously by rule 1 and rule 2 are removed and the generation process starts from the unfilled diagram of elements. The generative process starts by applying rule 1' to a decomposition line which involve the displacement of a mobile decomposition point (Figure 6.12b). As a consequence, two decomposition lines are left without one decomposition point. The application of rule 3 reconnects the decomposition lines with the mobile decomposition point (Figure 6.12c). This process continues until rule 1' and rule 2' are applied to all decomposition lines. Figure 6.12e shows how the diagram of elements has been modified by the application of decomposition rules. The sequence illustrated in Figure 6.12 reveals that changes on the outline of a represented design sometimes entail significant changes in the structure. Although designers may not be conscious of associated elements in hand-sketching, the definition of these elements in design computations is important. Mobile decomposition points provide valuable information on how a shape is perceived and therefore assist in generating designs that are consistent with the designer's intentions.

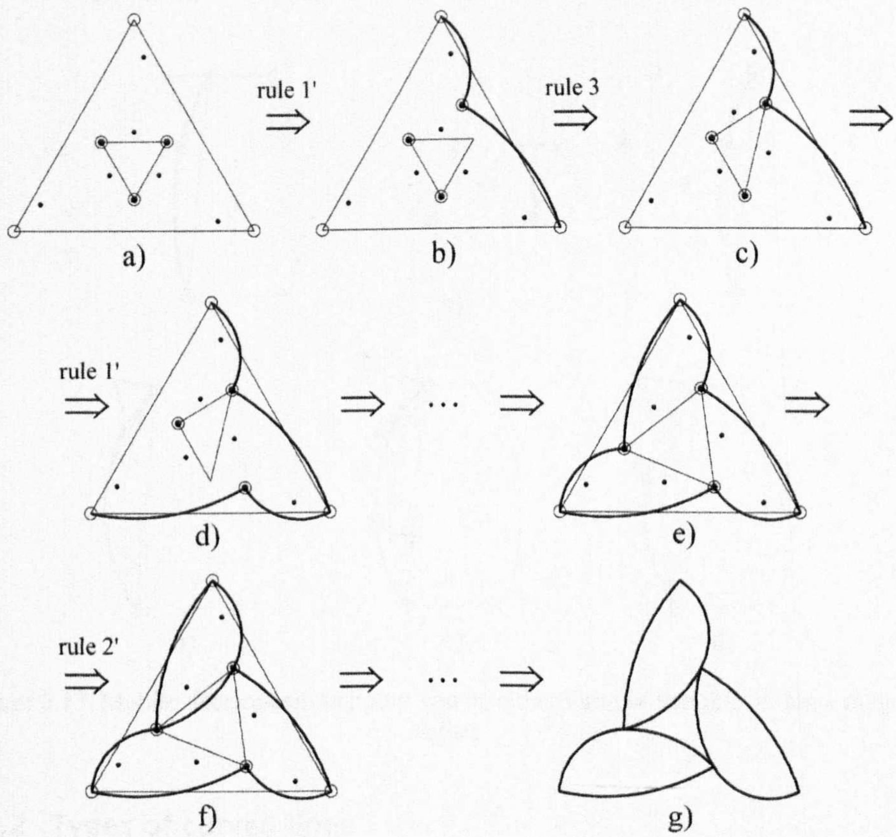


Figure 6.12. Successive applications of rule 1', rule 2', and rule 3 modify the diagram of elements

Mobile decomposition points, however, may not be placed at points of discontinuity as shown in the example above, but somewhere else in the outline. Taking the example of the kettle used earlier, consider the mobile decomposition point in Figure 6.13a, which connects the body and spout of a kettle. Once the parameters that represent the body of the kettle are modified, the spatial position of the spout also changes (Figure 6.13b). However, because the mobile decomposition point is not placed at a distinct point (e.g. point of discontinuity) it can be located anywhere in the interior of the outline (e.g. Figure 6.13c and d). The parameter R can be used to specify its location. Suppose that the outline of the body is made of 10 piecewise linear segments (R = 10), and that the mobile decomposition point is placed at the end of segment number 6. Thus, the position of the mobile decomposition point can be either fixed to segment 6 of the outline or variable within a range of segments (e.g. ± 3 segments from segment 6).

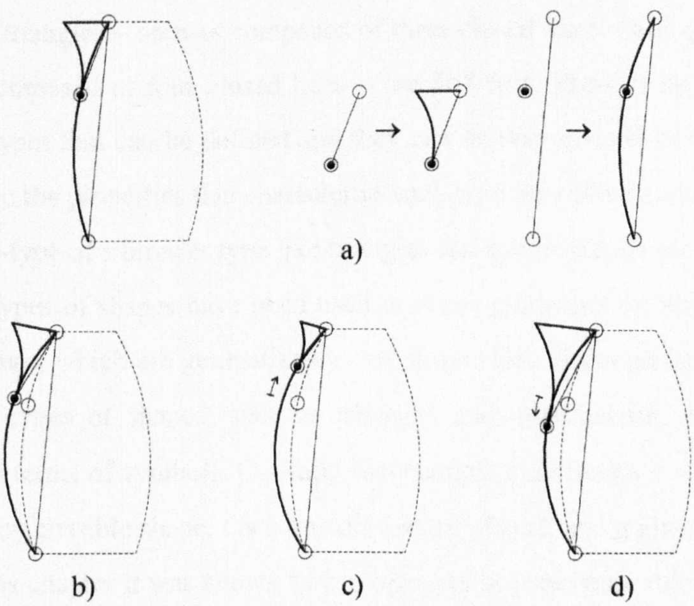


Figure 6.13. Mobile decomposition points can be either fixed or variable within a range of values

6.4.2 Types of curved lines

Shape rules do not always provide enough flexibility for the process of design exploration. They may require specific information about shape transformations that could be difficult to convey, especially in the early stage of the design process when ideas are still vague. For example, design alternatives can be generated from an initial concept design (e.g. Figure 6.12a) by transforming the rules that define that concept design (e.g. transform rule 1 and rule 2 into rule 1' and rule 2'); however rule transformations sometimes require the input of excessively specific values (e.g. values for ß, R, and Pd). One way of providing more flexibility to the generation process is by making shape rules more general. That is, allowing them to be applicable to different types of shapes instead of particular shapes. In order to do that, types of shapes need to be defined.

There have been many attempts to define types of shapes for the purpose of design. Types of shape are used to classify shapes that have similar properties such as triangles, quadrilaterals, and polygons. Here, properties refer to relations between elements that compose a shape. Thus, for example, the relations between elements of triangles – seen as composed of three closed lines – and quadrilaterals – seen as composed of four closed lines – are different. There is no limit on the number of types that can be defined and they can be very general or very specific depending on the properties that characterise each type. In addition, a type of shape can be a sub-type of a broader type like triangles and quadrilaterals are sub-types of polygons. Types of shapes have been used in shape grammars by Stiny (2006) to define schemas, which are generalizations of shape rules. Schemas can be applied to different types of shapes, such as triangles and quadrilateral, and they are expressed in terms of symbols. Consider for example the schema $x \rightarrow x + \mathrm{t}(\mathrm{g}(x))$, where x is any possible shape, t is a transformation of $\mathrm{g}(x)$, and g gives values to x. Earlier in this chapter it was shown how g operates in parametric rules. The shape rule illustrated in Figure 6.14 exemplifies the schema $x \rightarrow x + \mathrm{t}(\mathrm{g}(x))$ by inscribing a square in a square. The same schema can also be applied, among others, to quadrilaterals and triangles as shown in Figure 6.14. Observe that the inscribed shape is a transformation within the same type of the initial shape; quadrilaterals inscribe quadrilaterals, and triangles inscribe triangles.

Schemas can be very useful in the early stage of design exploration. They allow the transformation of shapes in a formal way, but without compromising designers by being too specific about transformations. Nonetheless, schemas become more complicated as soon as free-form shapes come into play. Unlike triangles, quadrilaterals, and polygons free-form shapes are more difficult to classify with types. Each free-form curve is unique.

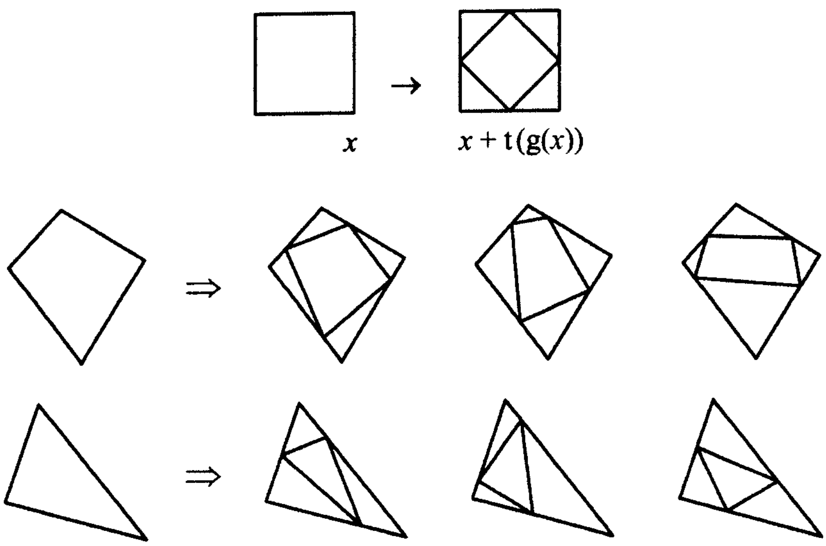


Figure 6.14. Schemas generalize the application of shape rules (Stiny 2006)

One way of classifying curved lines is by looking at their properties. Podehl (2002) in the FIORES project focuses on stylistic properties. He defines types of curved lines according to the terms used by designers to define curves such as hollow, tension, and acceleration. Each type of curved line is defined with different parameters that increase or decrease the hollowness of the curve, for example. As Podehl points out, these properties are highly subjective and depend on the context and designer. Therefore, in the design model developed by FIORES, each designer can define their own types of curved lines by assigning ranges of parameters. These stylistic properties can be very useful in the later stages of the design process, but may be unnecessary in the conceptual design stage since they demand a high level of detail.

Here, broader types of curved lines are presented with the purpose of describing some aspects of early design transformations. Recall that piecewise line-rules approximate the outlines by circular arcs, and that this simplifies the classification of types of curved lines. Disregarding the parameters of the arc (ß, R), one may define two types of arcs; concave and convex. That is, arcs where ß has a positive value and arcs where ß has a negative value. Different types of curved lines can be classified by considering lines composed of more that one circular arc. Each type will depend on the combination of concave and convex arcs. In other words, each type has different relations between the arcs that compose the curved line.

The concept of schema is here used in a narrower sense, referring only to curved lines composed of circular arcs. The top row in Figure 6.15 shows an example of a schema for curved lines; $(\beta, R)_1 \rightarrow g(\beta, R)_1 + g(-\beta, R)_2$, where g gives values to (ß, R). How the values in g are defined is discussed in Chapter 7. This schema can also be applied, among others, to different types of curved lines as shown in Figure 6.15; curved lines composed of one arc where ß has a positive value, and curved lines composed of two arcs that both have a positive value in ß. Note that the small thin lines on the curved lines indicate the point of connection between the arcs. Unlike the schemas presented by Stiny, schemas for curved lines do not have a transformation t because it is assumed here that the added arc is always connected tangentially to the previous arc.

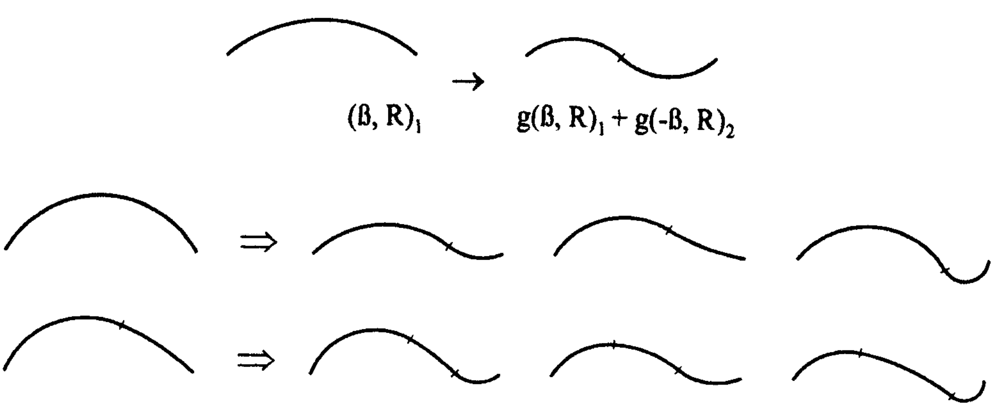


Figure 6.15. A schema for curved lines composed of circular arcs

A drawback of classifying types of curved lines through circular arcs is that sometimes curved lines of different types may be similar in appearance as Figure 6.16a illustrates. While the first curved line is composed of two circular arcs, the second one is composed of three circular arcs. Therefore, they are of different types. Although similarity in appearance between types can also occur with shapes made of straight lines, as shown in Figure 6.16b, their differences are easier to perceive than in curved lines.

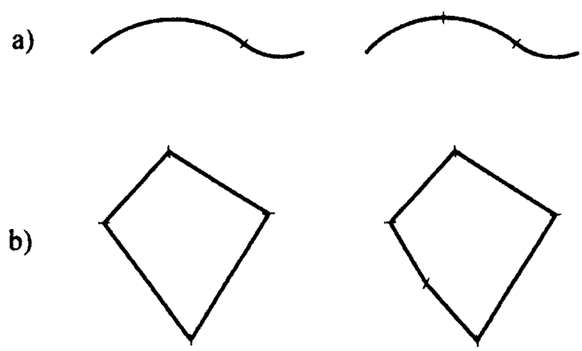


Figure 6.16. Shapes of different types may be similar in appearance

This section gives a list of five broad types of curved lines composed of two and three collinear arcs (Figure 6.17). This list, however, is not complete and more types of curved lines can be included, like outlines that contain straight lines and/or points of discontinuity. Figure 6.17 shows two possible types of curved lines composed of two circular arcs; (i) arcs with different signs for the value in ß and (ii) arcs with the same sign for the value in ß. And three possible types of curved lines composed of three circular arcs; (i) the arc in the middle has a different sign for the value in ß from the other two arcs, (ii) the arc in one extreme has a different sign for the value in ß from the other two, and (iii) all three arcs have the same sign for the value in ß.

Each schema can be distinguished by introducing small lines – the small thick lines on the left-side arcs of the schemas (they should be differentiated from the small thin lines that indicate the connection between arcs).

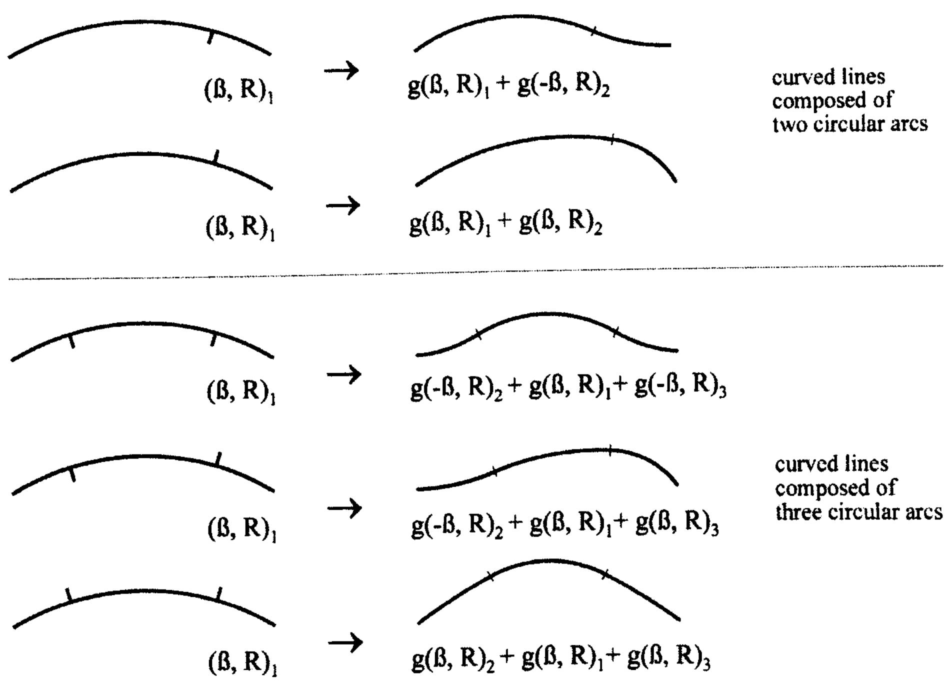


Figure 6.17. Five types of curved lines described in schemas

These thick lines are used to apply schemas to decomposition rules. The line indicates two things: first, the side on which the new circular arc is added; and second, the sign for the value in ß – the line pointing towards the centre of the circular arc indicates a different sign for the value in ß from the existing arc, whereas pointing away from the centre indicates the same sign for the value in ß.

In order to illustrate how schemas work during the process of generating designs via decomposition rules, the outline of a wine glass is taken as an example. Consider Figure 6.18 as an initial concept design. This example focuses on transformations of the body of the glass. Other elements of the wine glass such as the lip and foot will remain untransformed. A possible decomposition of the initial concept design is shown in Figure 6.19a. Once the decomposition points and decomposition lines are placed, three decomposition rules define the following elements: lip, body, and foot. Figure 6.19b shows the decomposition rule that defines the body.

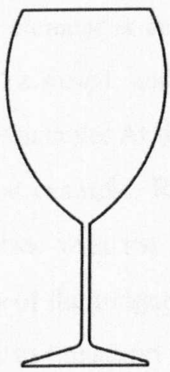


Figure 6.18. An initial concept design

As has been shown in Section 6.4, the values of the parameters (ß, R, Pd) are obtained from each element by approximating the outline with piecewise linear segments. In this example, the curved line that represents the body is composed of one single circular arc, and therefore does not have the parameter Pd. After introducing the labels in the decomposition lines, the decomposition rule is applied to the diagram of elements which redraws the initial concept design in a new layer (Figure 6.19c).

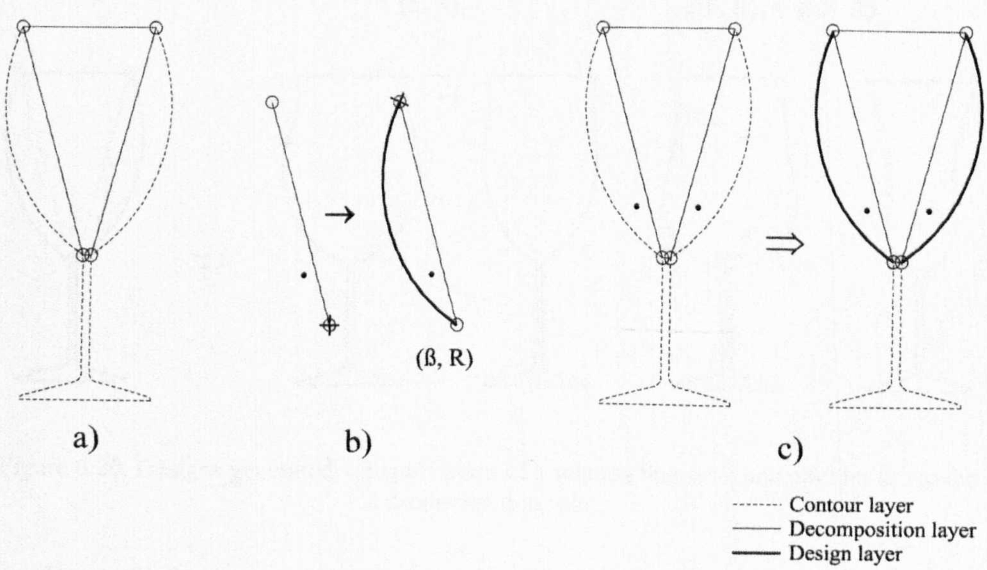


Figure 6.19. Definition and application of a decomposition rule

Now, new wine glasses can be explored by transforming the outline of the element body. This is done by giving new values to the parameters ß, R in the decomposition rule. Because this element is composed of one single circular arc the outline can only be flattened or raised, and therefore the designs that can be generated are very limited and predictable. At this point, one may want to explore more refined types of curves. For example, Riedel, one of the best wine glass companies, argues that wine glasses with the top of the body curved outwards directs the flow of wine to the tip of the tongue, the area where the perception of sweetness is the greatest. In order to transform the initial concept design into this kind of wine glass it is necessary to add an extra circular arc at the top of the body. This circular arc can be added to the outline by one of the schemas defined earlier. The schema is applied after introducing a thick line in the decomposition rule, as shown in Figure 6.20.

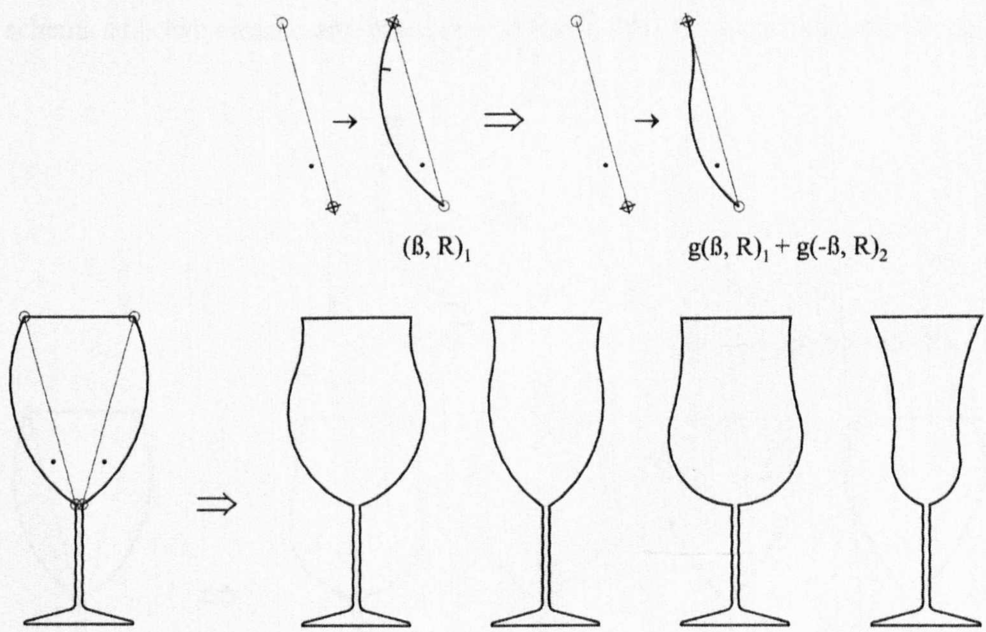


Figure 6.20. Designs generated via application of a schema that adds one circular arc to the decomposition rule

The applied schema adds a curve to the top of the body with a different sign for the value in ß from the existing circular arc. This schema generates not only one particular design but many designs that are composed of the same type of curved lines. Figure 6.20 shows four designs.

Once a schema is applied to the decomposition rule, it can generate a vast range of designs that share similar characteristics. All of them have the top of the body curved outwards. The group of designs represented in Figure 6.20 form, what is called here, a *design family*. A design family is a group of pictorial representations that are generated by applying particular sets of transformations to an initial concept design. This leads to the generation of a variety of designs that contain similar characteristics – Chapter 7 returns to the concept of design families.

If the previous set of transformations is replaced by a different set of transformations, then a new design family is formed. Suppose, for example, that a different schema is applied to the decomposition rule as shown in Figure 6.21. This schema adds two circular arcs to the curved line defined in the decomposition rule.

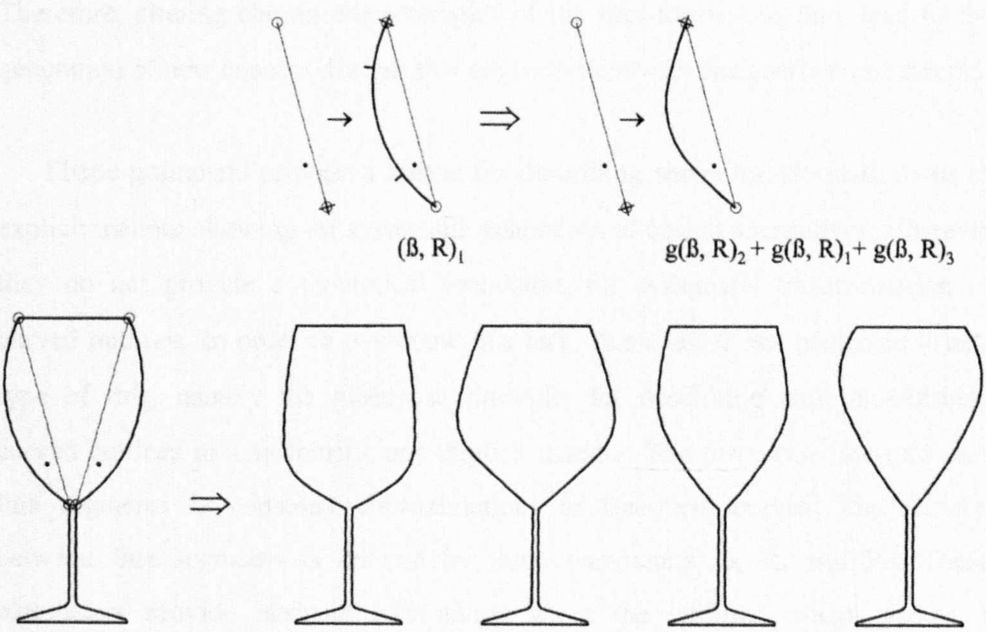


Figure 6.21. Designs generated designs via application of a schema that adds two circular arcs to the decomposition rule

Now, the decomposition rule generates designs where the outline of the body is composed of three arcs with the same sign for the value in ß. Figure 6.21 shows four examples. Comparing these designs with the designs in the previous figure, it is apparent that they belong to two different design families. However, not all similarities between different design families are so apparent, and it is in these cases where shape rules provide a valuable means for third-parties (including computers) to recognize some aspects of the designer's intentions.

6.5 Summary

The process of shape exploration in design is often realized by means of shape transformation. The sketches illustrated in Chapter 3 suggest that most concept designs are achieved by applying transformations to preceding concept designs. This means that the relation between two subsequent concept designs can be described in terms of shape transformations. Explicit descriptions of shape transformations can assist in capturing aspects of designers requirements. Therefore, altering certain characteristics of the transformations may lead to the generation of new concept designs that are consistent with designer's requirements.

Shape grammars provide a means for describing shape transformations in an explicit manner allowing for systematic generation of design alternatives. However, they do not provide a theoretical foundation for systematic transformation of curved outlines. In order to overcome this lack, this chapter has presented a new type of rule, namely the piecewise line-rule, for describing and transforming curved outlines in a systematic and explicit manner. The piecewise line-rule uses line segments to construct approximations of free-form curves. The relation between line segments is defined by three parameters; ß, R, and Pd. These parameters provide intrinsic information about the outlines, which makes it possible to generate a variety of curved outlines that share similar characteristics. This method offers a significant simplification when describing curved outlines, and increased effectiveness in transforming them without relying on complex mathematical equations.

Once piecewise line-rules, together with decomposition rules – presented in Chapter 5 – are in place to describe a concept design, this is ready to be transformed through the rules. The outlines of the design can be transformed in a controlled manner by altering the values of the parameters ß, R, and Pd. Because the outlines are attached to decomposition lines, which define the structure of the design, any set of values introduced to parameters of the outline will result in a new design that is consistent with the preceding designs, at least for the person who defines the structure.

This chapter has presented two significant features that assist designers in explicitly describing aspects of personal design requirements. One feature assists in describing perceptual associations between outlines of a design. The other provides flexibility and control over the process of exploring new outlines through decomposition rules. This allows the transformation of outlines according to requirements without being too specific about the values of parameters. The next chapter shows how piecewise line-rules, in cooperation with these two features, can assist the generation of families of designs that exhibit similar characteristics. The piecewise line-rules allow designers to specify the conditions and the degree of similarity between curved outlines according to their desires.

Chapter 7

Design spaces and design families

Overview

This chapter develops the concept of the *design family* which is considered to form part of a *design space*. Several aspects of generating design families through shape grammars are examined; particularly those shape grammars applicable to the field of product design. It is argued that design families can be used not only to analyze the possibilities and limits of classes of designs that have similar characteristics, but also in creatively exploring new design characteristics. This chapter describes how design families can be formalized through the descriptions presented in Chapter 5. Design families are generated by transforming two properties of shapes: (i) outlines and (ii) structures. In addition, this chapter shows how design families can be expanded, contracted, or displaced as design exploration advances.

7.1 Introduction

An important task in the process of designing a product is to generate shapes that satisfy a particular set of requirements. A design requirement is a goal that should be achieved by the design. Goel (1995) highlights the importance of personal preferences in determining the design requirements, which are also based on professional standards and practice, and consumer expectations. New design requirements are defined as the design process evolves and this act is strongly associated with creativity (Getzels and Csikszentmihalyi 1976). Often, design synthesis, especially through external representations, assists designers in defining new design requirements (Lawson 2006). At the same time design requirements assist designers in framing the generation process.

As discussed in Chapter 5, a plausible way to formally generate and analyse shapes is by decomposing them into parts of outlines. Generally, there is an endless variety of outlines that can satisfy all or most of the requirements and each combination of outlines can compose a shape that leads to a different design solution. Technically, all possible designs that meet a specific set of requirements may form a *design space*, including those designs that the designer is not satisfied with but satisfy the set of requirements. For example, constructing designs with traditional *Lego* bricks provide a simple illustration of the concept of design space.

Lego consists of a set of bricks of different types which can be assembled in numerous ways to form a variety of designs. Suppose that the only requirement is that the design has to be composed of a hundred bricks of a given type. In such case, the design space contains all possible designs that can be constructed with a hundred bricks. The design space can be expanded or contracted by modifying the requirements, as for example, bringing more or less bricks into play. The boundary of a design space (Figure 7.1a) depends on a set of requirements. Modifying them alters the boundaries of a design space; some requirements may contract the boundaries (Figure 7.1b) and others may expand them (Figure 7.1c).

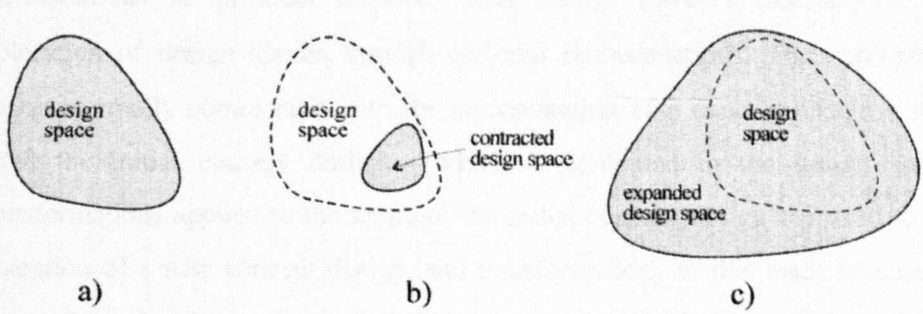


Figure 7.1. Design spaces can be expanded and contracted by modifying the set of requirements that defines it

Designing involves exploring design spaces. That is, designs that meet certain requirements. Design spaces tend to be immense and exploring them may be overwhelming, especially when dealing with numerous design requirements. A reasonable way to guide the exploration process is by reducing the space of possibilities. This can be done by constraining the requirements. For instance, going back to the example of *Lego* bricks, one may constrain the requirements by only considering those designs in which the bricks are assembled in a particular way. The modified requirements then define a contracted design space that is included in the original design space.

A situation that frequently occurs in design exploration is that, although the requirements are satisfied, the designer may not find any 'suitable' design in the design space. This may be solved by expanding the design space through adding new design requirements or changing the constraints of the existing ones. Such modifications can lead to a new design space that includes designs which may not have been possible earlier (Gero and Kumar 1993). That is, the whole or part of the new design space is set outside the boundaries of the initial design space, and therefore novel designs can be considered. Gero and Kumar suggest that establishing new design spaces outside of previous design spaces can assist in the development of creative designs.

A design space can be explored in several different ways (e.g. through mental representations or physical models). This thesis, however, focuses on the exploration of design spaces through pictorial representations. The exploration process normally commences with the representation of a concept design – here called the initial concept design – which is contained in the design space. Transformations applied to the shape of the initial concept design will lead to the generation of a new concept design, and transformations of this leads to another new concept designs, and so on. If the chosen path does not lead to a 'suitable' design, the designer may backtrack to a previous concept design and then commences a new path by applying different transformations. If the transformations are in accordance with requirements, the generated concept designs will all belong to the same design space. The set of all graphically represented concept designs that form part of the same design space are here referred to as a *design family*.

A design family represents a particular design space. If two or more separate sets of designs are generated from the same design space they form a unique design family. That is to say that two design families cannot represent the same design space. They either are the same design family or represent different design spaces. Designers gain knowledge of a design space by generation of a design family. The bigger the design family the more accurate their knowledge is. In practice, however, designers may generate only a few pictorial representations of the concept designs included in a design space. It is possible that designers may explore more concept designs than those graphically represented, which might be explored through mental representations. This suggests that designers do not employ more pictorial representations in design exploration because they are time-consuming compared to mental representations. Automatic generation of design families could enhance design exploration; not by making the process shorter, but in terms of being able to consider more concept designs in pictorial representations which may assist the establishment of 'better' requirements and therefore to obtain 'better' designs.

Figure 7.2 schematically shows two paths that a designer may trace during exploration of concept designs. The points represent depicted concept designs that form part of one or more design spaces – note that different design spaces can contain the same concept design. The arrows indicate the sequence in which the concept designs are generated. The first path exemplifies the process of generating concept designs through hand sketches (Figure 7.2a), and the second path through automated generation by a computer (Figure 7.2b). In both examples the path begins in one design space (Ds 1) and ends in another design space (Ds 2). While in the first path the designer only considers three concept designs, in the second path a larger variety of concept designs is considered. Figure 7.2b shows that the original path may be altered if an automatically generated concept design is considered more 'suitable' than the previous one. This example shows that automatic generation of design families can influence the paths traced by designers leading to more 'suitable' concept designs that may not be considered through informal exploration (e.g. hand-sketches).

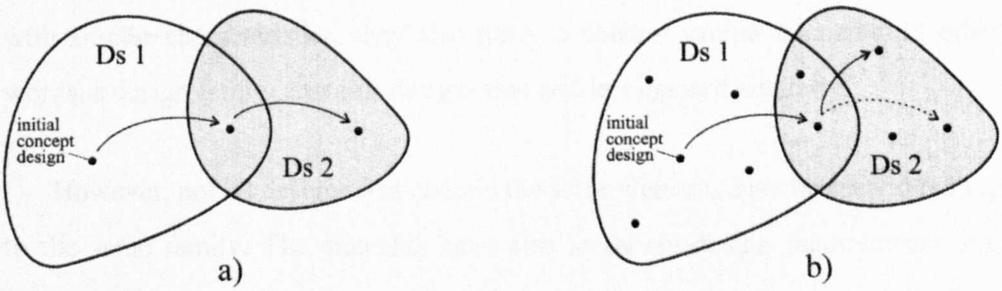


Figure 7.2. Path traced by the designer in concept design generation through: (a) hand-sketches and (b) automatic computation

7.2 What a design family is

Providing a clear definition of design family is not easy and is open to many interpretations. Broadly, a family is a 'group of related things'. Parents and their children are commonly considered to form a family, but if a group of people – even if they do not have blood relations – share common interests or attitudes also can be considered a family. In products the concept of family is also fluid; a group of products that contain similar characteristics can be considered to be in the same family. Note that design characteristics are meant to contribute to achieving design requirements. Similarly, sequences of sketches produced by designers during design exploration also seem to form families. However, in design sketches, it is unclear which characteristics are taken to form a design family. As it has been observed in the empirical study presented in Chapter 3, a sequence of sketches may appear to contain different characteristics but the participant may claim that they belong to the same design family, and vice versa. This suggests that designers see some characteristics in their sketches that are not apparent to an outside observer.

Similar characteristics between shapes can be identified if they contain the same perceived elements – that is to say that they are decomposed similarly. The example of the swords-mice used by Van Sommers illustrated in Chapter 2 demonstrates that different decompositions of the same shape lead to the perception of different characteristics. The crossed swords contain two straight lines and the two mice two 'V' shapes. Thus, if a design family contains designs with similar characteristics, they also have to contain similar elements. In other words, a design family contains designs that are decomposed similarly.

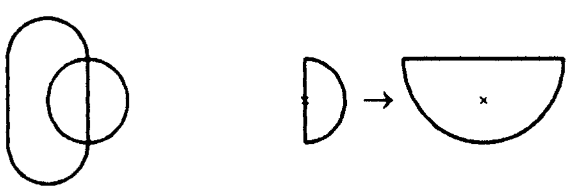
However, not all designs that contain the same elements may be seen to belong to the same family. The elements have also to satisfy design requirements. For instance, taking again the example of the two crossed swords used by Van Sommers, a requirement could stipulate that the swords have to cross on their midpoints. Thus, any composition of two swords that do not cross on their midpoints is not considered to belong to the design family. Therefore, a design family is a group of shapes that are decomposed similarly and satisfy the same requirements.

Design families contain similar designs, although the kind of similarity is distinguished from similarities based on shared features (Tversky 1977). The relations between designs in a family are transformations of the outlines within the same decomposition. In other words, designs in the same design family share similar elements. Design families can be generated in a systematic way which provides control in the exploration process. As Mitchell (1990, p.181) says "design exploration is rarely indiscriminate trial-and-error but is more usually guided by the designer's knowledge of how to efficiently put various types of compositions together and that such knowledge can often be made explicit, in a concise and uniform format, by writing down shape rules".

In order to explore design spaces in an explicit format, design requirements need to be described explicitly. Shape rules provide a plausible way to explicitly describe architectural and product design requirements, though other means may be also efficient in other fields such as the grids used by Thompson (1942) to generate families of fish and vertebrate skulls. Shape grammars have shown that a set of shape rules defines a design space and also they can generate design families within the design space. It should be noted that while the design space is defined 'intensionally' by shape rules, the design family is defined 'extensionally' by the generated designs.

7.3 Design families and shape grammars

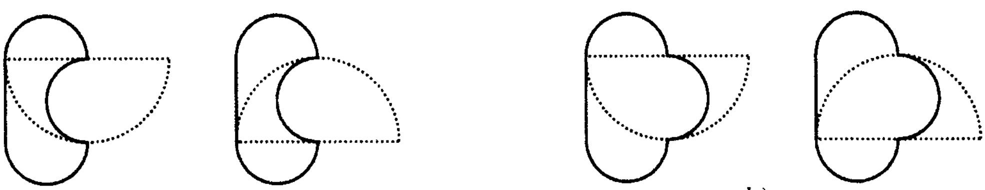
Shape grammars provide a means for generating design families according to sets of requirements which are explicitly defined through shape rules. These requirements are not always easy to put into rules, especially qualitative requirements such as 'easy to use', 'elegant looking', and the like. Hence, shape grammars normally consider only geometric requirements such as parallels and symmetries. In addition, sometimes shape rules are complemented with short verbal descriptions (e.g. to state the number of times that a rule can be applied). As an example of a geometric requirements, consider the initial design shown in Figure 7.3a and the shape rule in Figure 7.3b, which rotates and scales a crescent shape.



a) b)

Figure 7.3. (a) An initial design and (b) a shape rule

Another design requirement may limit the application of the rule to one iteration only. In this case, the rule can only generate four concept designs (Figure 7.4). Observe that the initial design contains two crescent shapes which are similar to the shape in the left-hand side of the rule. Therefore, the rule has two starting points. In addition, because of the symmetrical properties of the crescent it is possible to apply the rule in two different directions. However, observe that the two crescent shapes share a part of the outline which means that the rule can only be applied to one of them – one crescent disappears after application of the rule to the other crescent. What occurs here is that the rule is applied according to two different interpretations of the initial design. That is, two different sets of elements. Figure 7.4 illustrates the two possible applications of the rule for each interpretation. Different line styles are used to distinguish between elements that compose each design.



a) b)

Figure 7.4. Two different design families

To define a grammar that generates successive designs from an initial design within several design spaces is not straightforward. The example shown in Figure 7.3 has been carefully devised for the purpose of generating designs in more than one design space. In order to devise such types of grammars it is necessary that a transformation of a shape element results in an emergent shape element that is already defined in an existing rule. Thus, the rule can be applied again, leading to a new design. This condition may be difficult to achieve for certain type of shapes, especially for non-symmetric shapes, shapes that do not contain repeated elements, and shapes without crossing lines.

Despite this drawback, what is interesting in this example, in addition to previous efforts, is that it shows that one shape rule (or few shape rules) can generate designs from different design spaces. If we consider that design spaces contain only designs composed of the same elements, then the designs in Figure 7.4a and the designs in Figure 7.4b belong to two different design spaces because they are composed of different pairs of elements. That is to say that the two pairs of designs form two different design families. However, since the shape represented in continuous line is not formalized in a rule, it is up to the observer to decide whether or not they are different. If the shape is interpreted as a closed outline (Figure 7.5a) then they are different, but if interpreted as composed of two outlines (Figure 7.5b) then they may be similar.

Figure 7.5. Different interpretations

Each of these design spaces can be expanded by allowing more than one application of the rule. Observe in Figure 7.4 that a new crescent shape emerges in each design. Again, new interpretations come into play because the transformed crescent shape and the emergent crescent shape share a part of outline. This implies that a new design space is defined after reinterpretation of the design. Figure 7.6 shows a variety of designs generated by allowing up to six applications of the rule. This group of designs does not form one design space but several design spaces because not all designs can be decomposed into the same elements.

The example used here attempts to demonstrate two things. First, that shape grammars can generate designs outside of their initial design spaces -- this is a crucial aspect for creative design. And second, that the reinterpretation of designs during the generative process is triggered by the grammar itself after a rule is applied to an emergent shape, though emergent shapes are not always involved in reinterpretation of the design. This means that the transition between design spaces may be done by the computer and as a consequence the control of the designer over the design process is reduced. To some extent, this is what makes shape grammars especially attractive when applied in design exploration -- the grammar can generate unexpected yet interesting designs with little or no assistance from designers. However, designers may sometimes want to take control of the design process – especially when a promising design is identified – but at the same time allowing the computer to generate design alternatives of the same idea.

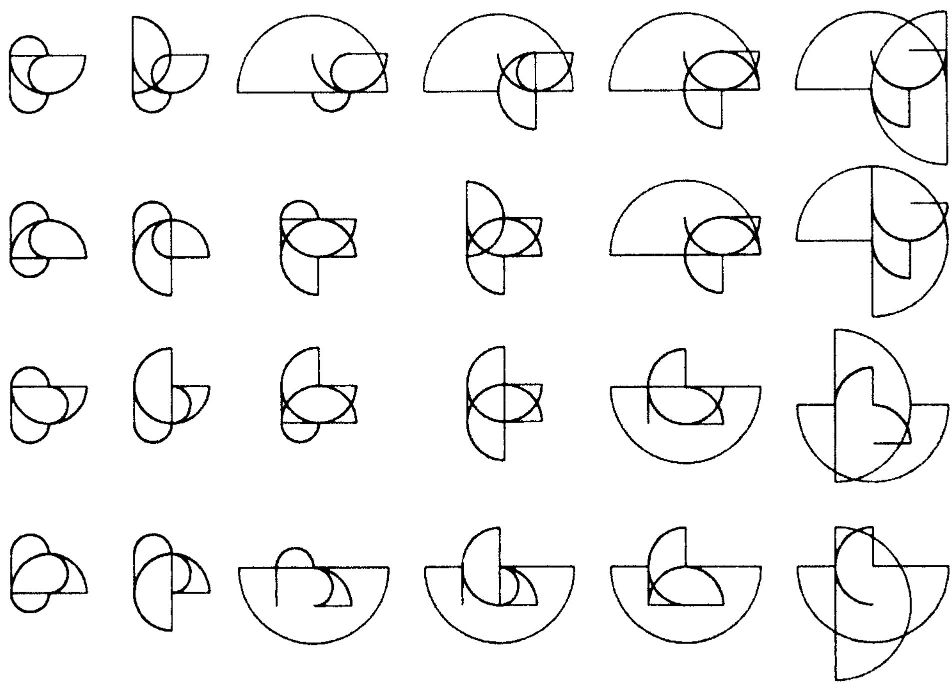


Figure 7.6. Designs generated by allowing up to six applications of the rule starting from the initial design

Different types of shape grammars implementations have demonstrated that it is feasible to provide more control of the generative process. Unlike the example used above, some grammars are not meant to generate abstract designs but generate meaningful ones such as buildings and consumer products. In the field of product design, several shape grammars have been devised in order to generate consumer products including coffeemakers (Agarwal and Cagan 1998), motorcycles (Pugliese and Cagan 2002), cars (McCormack et al. 2004), and packaging (Hau et al. 2004). These grammars operate in a rather different manner from the grammars examined above. One significant difference is that they generate design by transforming the outlines of the elements instead of the spatial position of the elements.

The coffeemaker grammar (1998) is one of the earliest implementations to use shape grammars to generate a type of consumer product. This grammar consists of a hundred parametric rules which define the requirements of three basic elements that compose the coffeemaker, namely the filter, water storage container, and base. A design family of coffeemakers is generated by assigning values to predefined parameters. These parameters then define the outlines for each of the three basic elements. This assists the generation of coffemakers in the same style. Figure 7.7 illustrates four concept designs.

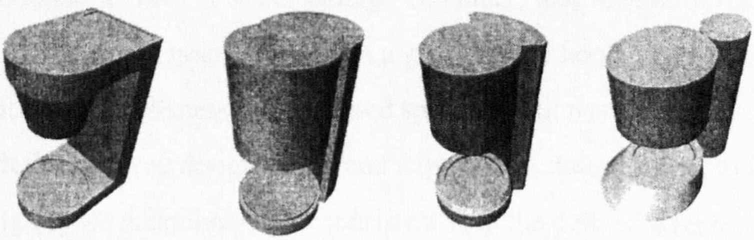


Figure 7.7. A design family generated through the coffeemaker grammar (Agarwal and Cagan 1998)

Similar to the coffeemaker grammar, the Buick grammar (2004) defines one particular design space, which encapsulates some aspects of the Buick brand. This grammar generates pictorial representations of front-ends of Buick cars which are all decomposed into the same elements. Each element is defined in a set of parameterized rules that transform the outlines made of free-form curves. The manipulation of such curves is restricted to predefined parameters and as a result the designer cannot generate designs outside the design space. In order to obtain designs that are consistent with the brand, the grammar generates designs with a fixed structure. Figure 7.8 illustrates a design family generated via the Buick grammar.

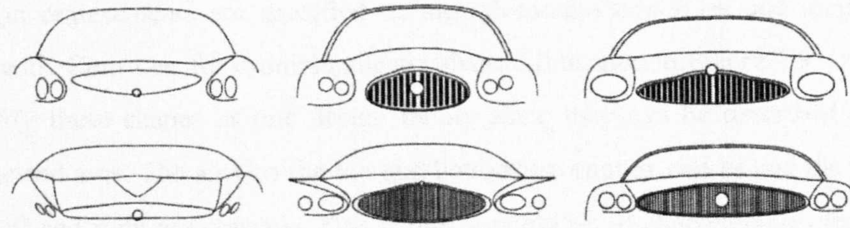


Figure 7.8. A design family generated through the Buick grammar (McCormack et al. 2004)

The examples in Figure 7.7 and Figure 7.8 show that in order to explain a particular style or brand through shape rules it is necessary to maintain the elements of a design. For example, all designs generated by the coffeemaker grammar contain a filter, a water storage container, and a base; all the designs generated by the Buick grammar contain a grill, middle hood, and fenders, among other elements. Each element has a defined spatial position and type of outline. The grammar defines a fixed design space, and any concept design that does not belong to this design space is unlikely to be consistent with the defined style or brand. The research described in this thesis has been concerned with devising a method for generating design families with the purpose of exploring a defined design space – similar to the coffeemaker grammar and Buick grammar – but also exploring new design spaces. This is crucial to allowing creatively generated new designs. This chapter describes how design spaces can be explored in an explicit and controlled manner through generation of design families. To do this, design families are generated by transforming two properties of shapes: (i) outlines and (ii) structures.

7.4 Design families to explore design spaces

One way to identify whether or not a set of designs form part of the same design family is by using formal descriptions; this can take the form of shape rules. Here decomposition rules are used to describe designs. If each design in a set can be described via the same decomposition rules, then those designs form one design family. Recall that decomposition rules are applied to a diagram of elements defined to an initial shape; therefore, designs in a family preserve the same diagram.

Design requirements are specified through decomposition rules and diagram of elements. Consider, for example, the six shapes illustrated in Figure 7.9. One may identify these shapes as one design family since they can be described as four connected arcs. The arcs on the top and bottom are convex curves and the arcs on the left and right are concave. This is one possible set of characteristics that leads to identify all these shapes as one design family.

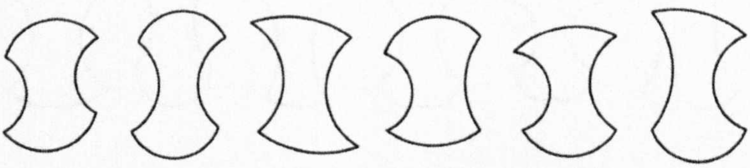


Figure 7.9. This group of designs may be identified as one design family

However, different characteristics can also be identified. Observe that some of these shapes – the first three from the left – possess a diagonal axis of symmetry. Figure 7.10 shows a decomposition rule that describes these shapes, which are named as design family 'A'. The rule and diagram of elements – in this case composed of one straight line – that describe these designs are composed of two rotationally symmetric elements. The remaining designs – the first three from the right – are described by two decomposition rules. These designs, called design family 'B', are composed of three elements different from design family 'A'.

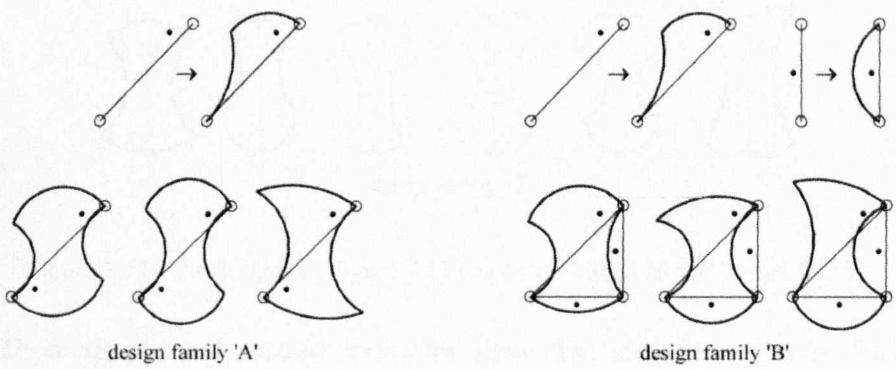


Figure 7.10. The designs in Figure 7.9 can be described as two different design families

Consider now a new group of shapes that clearly exhibits different characteristics from one another, such as the shapes in Figure 7.11. One may identify these shapes as two different design families because they exhibit different characteristics: some designs are composed of four arcs and others composed of six arcs.

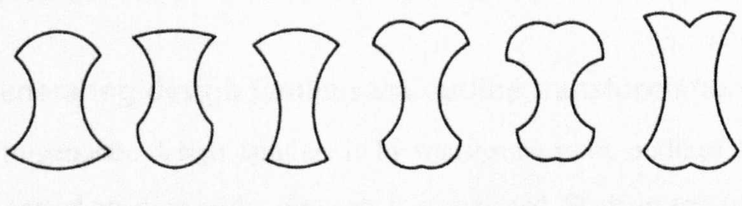


Figure 7.11. This group of designs may be identified as two different design families

Similar to the group of shapes given earlier, it is possible to identify different characteristics in the shapes in Figure 7.11. Observe that all of them contain a vertical axis of symmetry. Figure 7.12 shows the decomposition rule that describes these shapes, which reveal that these shapes are composed of one element repeated two times.

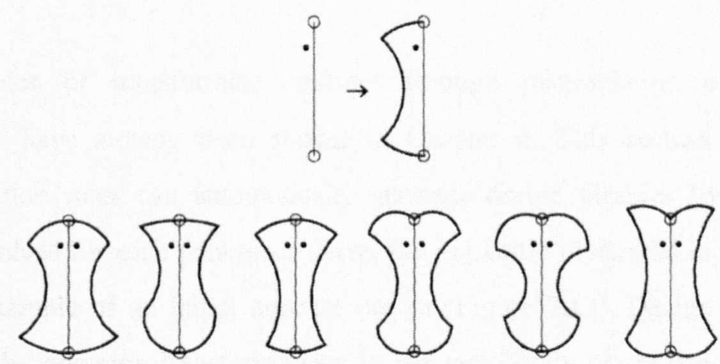


Figure 7.12. The designs in Figure 7.11 can be described as one design family

These simple and abstract examples show that identifying design families depends on the interpretations of the observer. This is similar to defining design spaces. Shapes with apparently similar characteristics can be identified as different design families, and on the contrary, shapes with apparently different characteristics can be identified as one design family. The examples show that decomposition rules provide a plausible means for defining design requirements through pictorial representations of designs. If decomposition rules are defined by a designer during design exploration, then other people (as well as computers) can generate novel designs that will be consistent with the designer's requirements, that is, designs that will be part of the same design family.

7.4.1 Generating design families via outline transformations

One way to generate design families is by transforming the outlines of elements whilst the spatial position of the elements is maintained. Such an approach is often used by designers, especially through overtracing their sketches. As Do and Gross (1996) suggest, one of the functions of overtracing sketches is shape refining. Thus, one single sketch is sometimes used to generate a variety of concept designs by applying transformations to outlines. Decomposition rules can assist in generating concept designs consistently with this approach. Unlike hand sketches, however, decomposition rules display each refined concept design in a new pictorial representation.

Examples of transforming outlines through manipulation of piecewise parameters have already been shown in Chapter 6. This section shows how decomposition rules can automatically generate design families by selecting a range of values for each parameter. Here, the jug kettle illustrated in Chapter 5 is used as example of an initial concept design (Figure 7.13). Design families are generated by applying transformations to the main body of the kettle while the outlines that define the handle and spout are kept fixed.

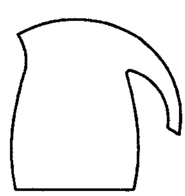


Figure 7.13. Initial concept design

As discussed in Chapter 5, this concept design can be decomposed in many different ways. Moreover, it is possible to interpret elements that are not fully represented in the design. For example, the outlines that represent the main body of the kettle may be extended beyond the handle and spout. This is a type of emergence based on transformational processes discussed in section 3.3.2, in Chapter 3. These emergent shapes, which are visually suggested by the outlines but not fully represented, can be completed through shape rules. Figure 7.14 shows a possible shape rule, which extends a line to meet another line, and three designs generated after application of the rule to the initial concept design.

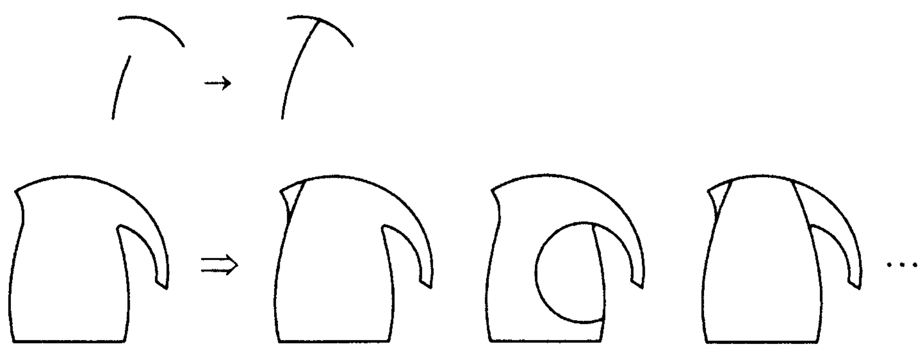


Figure 7.14. Designs generated by a rule that extends a line to meet another line

Each of these concept designs suggests different perceptual decompositions and therefore each of them offers starting points that will lead to different design spaces. Figure 7.15a shows the chosen concept design and a possible decomposition by placing decomposition points (Figure 7.15b) and decomposition lines (Figure 7.15c). Observe that two mobile decomposition points – refer to Chapter 6 for details – have been placed in order to indicate that the handle and spout are connected with the body of the kettle. Hence, any variation in the outline of the main body will result in a modification of the handle and spout. Figure 7.15d illustrates the rule that defines the outline of the main body and the values of its parameters. This outline is composed of two circular arcs. Note that the rules that define the rest of the kettle are not shown in the figure.

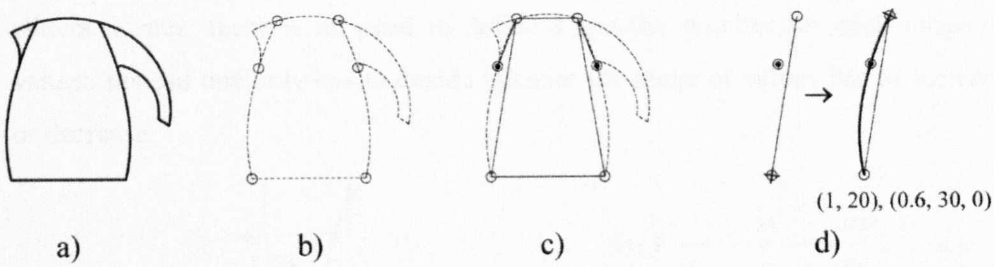


Figure 7.15. (a) Chosen concept design, (b) addition of decomposition points, (c) addition of decomposition lines, and (d) definition of the decomposition rule

The outline of the body of the kettle is composed of two arcs; $(ß, R)_1$ with values (1, 20) and $(ß, R, Pd)_2$ with values (0.6, 30, 0). Recall that because the value of Pd is 0, the connection between arcs is tangential. The cross in the decomposition point (Figure 7.15d) indicates that the first arc is attached to the base of the kettle and the second one is attached to the lid. New outlines can be generated by altering one or more values of the parameters. One set of values generates one single design. However, it is possible to give a range of values for each parameter. By doing this, a decomposition rule can generate a design family within the range of values that are randomly chosen by the computer. For example, suppose that the value of $ß_1$ is not 1 but any value from -1.5 to 3.5. Such range of values can generate a design family with variations in the lower part of the body of the kettle. The outline can be transformed in numerous different ways by giving a range of values to each parameter as the design family shows in Figure 7.16, named 'design family 1'.

The values of the parameters can be used as a way to encode design transformations in an explicit manner, which can provide valuable information in understanding aspects of designers' moves. However, entering a value for each parameter may frustrate the exploration flow because it is time consuming. In addition, designers tend to express their ideas in a visual and graphical way instead of in a numerical way. One of the reasons why most CAD systems do not provide enough flexibility in conceptual design is because they rely on numerical values. In order to avoid dealing directly with numbers, the range of values can be defined via sliders. Hence, there is no need to define a specific number for each range of values; instead one only has to decide whether the range of values has to increase or decrease.

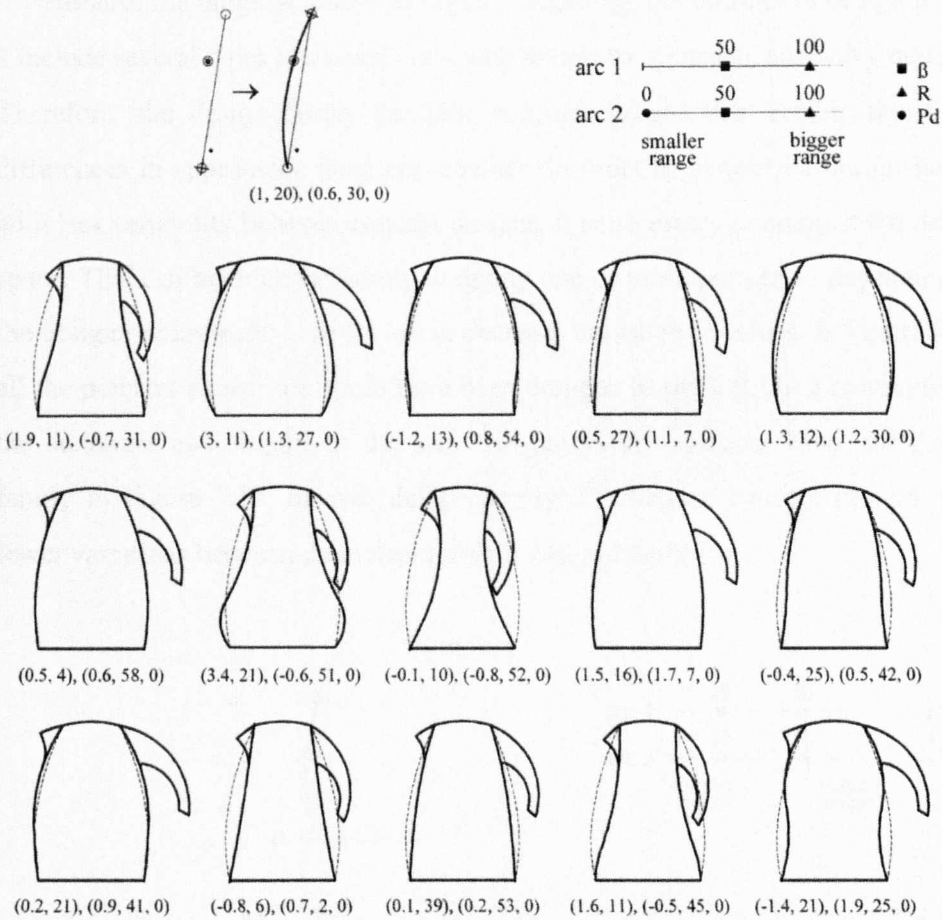


Figure 7.16. Design family 1

Each circular arc in an outline corresponds with a slider where the range of values of ß, R, and Pd can be either increased or decreased. For instance, if one expects to obtain outlines with smoother connections between the arcs that compose them, the slider Pd should be moved towards 0. Figure 7.16 shows the decomposition rule that describes the body of the kettle and its sliders. There are two sliders because the outline is composed of two arcs. Each slider has more than one pointer; a square is used to indicate the position of ß along the slider, a triangle the position of R, and a circle the position of Pd. The numbers displayed on each pointer are not meant to be used by designers but are used to explicitly define the boundaries of design spaces. This will be examined later in this section.

Because the range of values in Figure 7.16 is big, the outlines in design family 1 include several types of curved lines such as convex, concave, and wavy outlines. Therefore, the design family contains concept designs that exhibit significant differences in appearance from one another. In order to generate a design family with less variability between concept designs, it is necessary to contract the design space. This can be done by simply dragging one or more pointers – depending on the design requirements – to the left to decrease the range of values. In Figure 7.17, all the pointers except the circle have been dragged to the left. As a consequence, the curvature and lengths of the arcs will have less variation. Now, the design family in Figure 7.17, named 'design family 2', contains concept designs with fewer variations between them than those in design family 1.

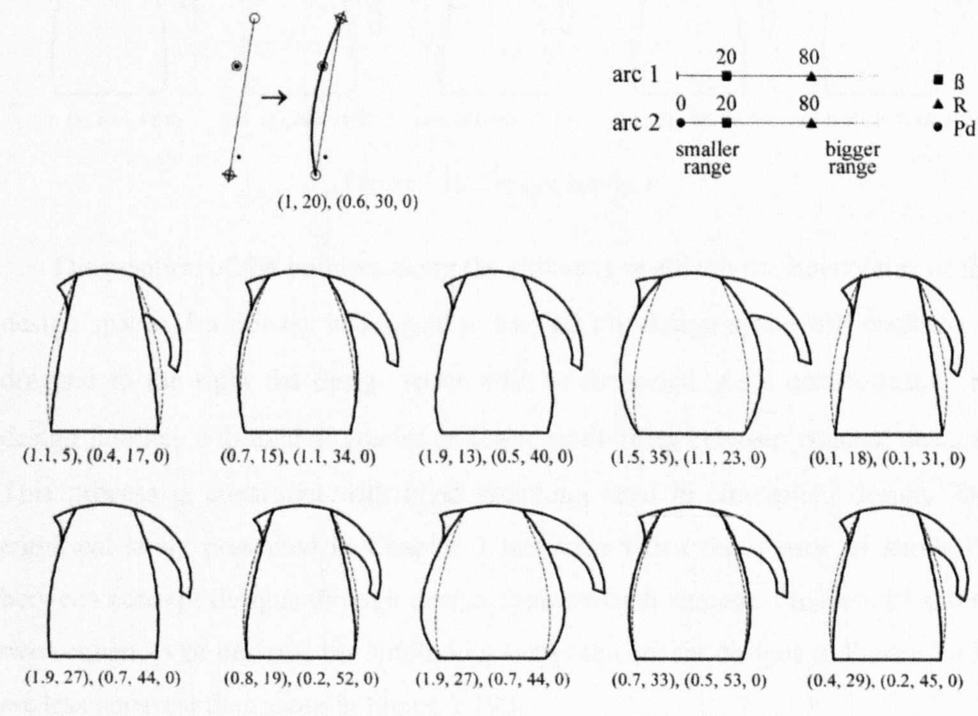


Figure 7.17. Design family 2

This design space can be contracted once more by dragging the pointers again to the left. The design family in Figure 7.18, named 'design family 3', contains concept designs with almost no variations between them. The less freedom allowed to the parameters, the more similar the design concepts will be according to requirements. The random generation of designs by computer allows the fast generation of a large range of concept designs for the designer to explore, some of which may otherwise have been overlooked. The position of the sliders can be used to guide the generative process by giving more or less freedom to parameters.

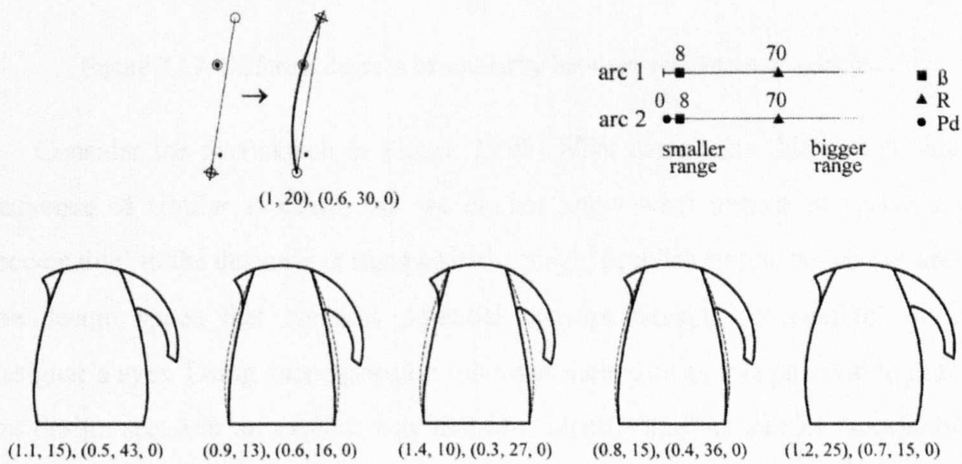
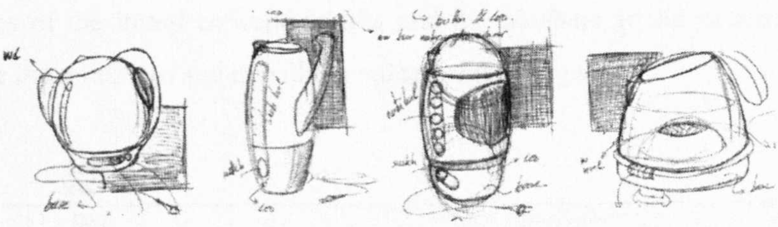
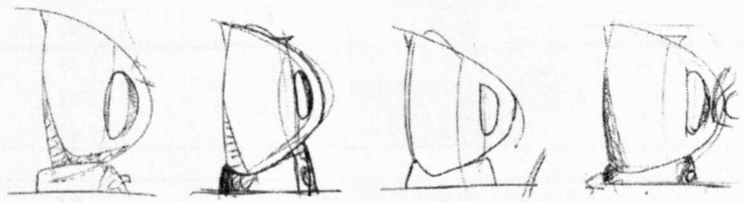


Figure 7.18. Design family 3

The position of the pointers along the sliders is related to the boundaries of the design space. If a pointer is dragged to the left the design space will contract; if dragged to the right the design space will be expanded. As a consequence, the design families will exhibit greater or fewer similarities between concept designs. This process is consistent with hand sketching used in conceptual design. The empirical study presented in Chapter 3 has shown that the degree of similarity between concept designs through design exploration fluctuates. Figure 7.19 shows two sequences of designs; the similarities between concept designs in Figure 7.19a are less apparent than those in Figure 7.19b.



a)



b)

Figure 7.19. Different degrees of similarity between sequences of sketches

Consider the first sketch in Figure 7.19b. What came after this sketch was a sequence of similar sketches, but we do not know what degree of variation is 'acceptable' to the designer at that particular stage. In other words, we do not know the design space that contains potential concept designs 'acceptable' in the designer's eyes. Using decomposition rules and their sliders, it is possible to define the design space in an explicit way and also identify the number of 'acceptable' concept designs that form that design space. Consider for example the design family 1 in Figure 7.16. The position of the pointer ß$_1$ in the slider (the square in arc 1) is at 50. This value gives a range of ± 50 degrees to the angle α of the circular arc (recall that α = ß x R). Therefore, since ß = 1 and R = 20, the range of values for ß is from -1.5 to 3.5. The position of the pointer R_1 in the slider (the triangle in arc 1) is at 100. This value gives a range of ± 100 percent of R to R. Then, the range of values for R (R = 20) is from 0 to 40. The equations that give ranges to ß and R are not sensitive to the number of line segments used to construct a curved line. Hence, a particular value will produce the same consequences for a curved line composed of few line segments as another one composed of numerous line segments. The Table 7.1 shows the range of values for each parameter (ß, R, and Pd) in each design space (Ds 1, Ds 2, and Ds 3). The numbers in the boxes are the values of the initial concept design, and the numbers at the extremes of the boxes are the minimum and maximum values of the ranges.

	design space			
$ß_1$	Ds 1	-1.5	1	3.5
	Ds 2	0	1	2
	Ds 3	0.6	1	1.4
R_1	Ds 1	0	20	40
	Ds 2	4	20	36
	Ds 3	10	20	30
$ß_2$	Ds 1	-1	0.6	2.3
	Ds 2	-0.1	0.6	1.3
	Ds 3	0.3	0.6	0.8
R_2	Ds 1	0	30	60
	Ds 2	6	30	54
	Ds 3	15	30	45
Pd_2	Ds 1		0	
	Ds 2		0	
	Ds 3		0	

Table 7.1. Range of values for each parameter in design spaces Ds 1, Ds 2, and Ds 3

Table 7.1 shows that, in design space 1, the range of values for $ß_1$ is from -1.5 to 3.5, R_1 is from 0 to 40, $ß_2$ is from -1 to 2.3, and R_2 is from 0 to 60. Note that Pd is kept at 0 because there is no range of values assigned to it. Such ranges of values define the boundaries of the design space 1. Thus, for example, if the value of $ß_1$ in a generated concept design is 2.5, the design will be in design family 1, but not in design family 2 and design family 3. The ranges of values provide information about whether or not a design is in a design space, but they also provide more information; the number of designs that are included in a particular design space. Here, only values with one decimal are considered but more decimals can be attained. Including the two extreme values, $ß_1$ has 51 possible values, R_1 has 41, $ß_2$ has 34, and R_2 has 61. Therefore, design space 1 contains 51 x 41 x 34 x 61 = 4,336,734 different concept designs. Fewer concept designs are contained in design space 2 (509,355), and design space 3 (35,154). These numbers themselves do not provide any significant information to designers but they allow a representation of the boundaries of each design space in a schematic way. Design space 2 shares approximately 12 percent of the area of Ds 1, and Ds 3 less than 1 per cent of Ds 1. Figure 7.20 illustrates a schematic representation of these three design spaces, which clearly shows that the Ds 2 and Ds 3 are contracted design spaces from Ds 1.

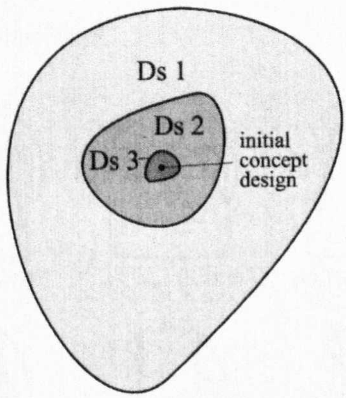


Figure 7.20. Schematic representation of design space 1, 2, and 3

It has been shown that design spaces can be expanded or contracted from an initial concept design. However, this rarely occurs in design exploration. Instead, designers normally set new requirements as the generation of sketches progresses. Each concept design follows the previous one rather than the initial concept design. When the designer cannot find any satisfactory design in the defined design space, it is necessary to expand it or to define a new one outside the initial design space.

Consider now that a designer wants to explore a design that is included in design family 1. Figure 7.21 shows the chosen concept design. Observe that the characteristics of the outline have changed from the initial concept design. While the outline of the initial concept design was composed of two circular arcs with the same sign, the outline of the chosen concept design is composed of two arcs with opposed signs – which creates a wavy outline. The values of the parameters obtained from the chosen concept design can be kept and used to generate a new design family that resembles that design. Figure 7.21 shows that the position of the sliders has been dragged to the left in order to reduce the design space, and therefore generate designs with less variation and more similarity to the chosen concept design.

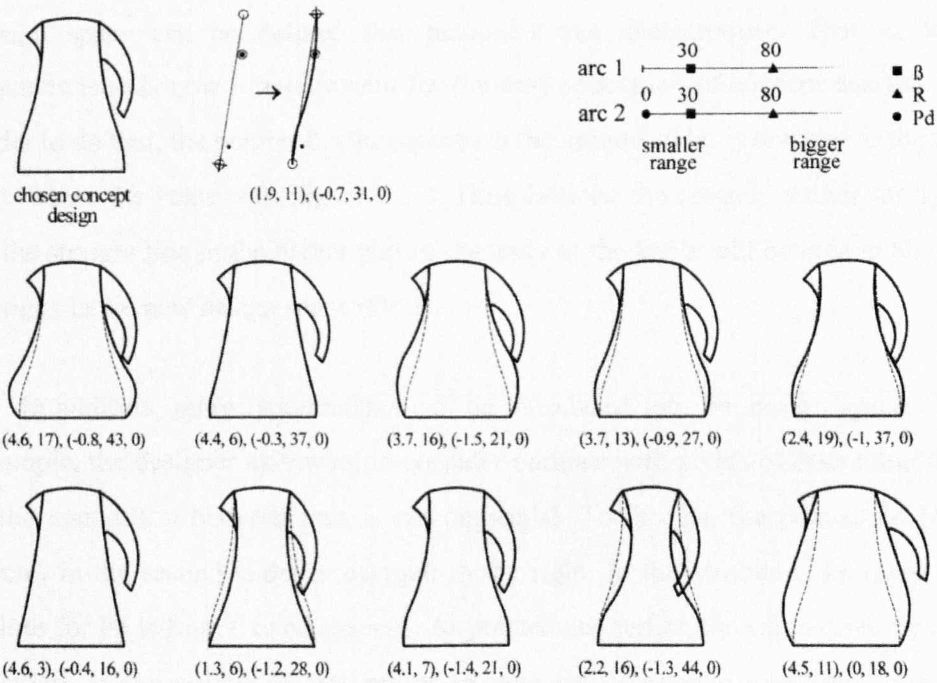


Figure 7.21. Design family 4

The design family in Figure 7.21 – called design family 4 – differs from the three previous design families in that the values of the parameters are not taken from the initial concept design but from a chosen concept design. The ranges of values in the chosen concept design define a new design space (Ds 4) that is set outside of the initial concept design. In other words, the initial concept design is not included in the new design family. In addition, the ranges of values are wide enough to define a displaced design space that includes designs that were not possible to generate earlier.

This process is consistent with designers' moves in which new requirements are established after the generation of each concept design. For example, after the generation of design family 4 designers may chose one concept design and generate a new design family from that design. Suppose that the chosen design is the first kettle from the right, in the second row. A particular characteristic of the outline of this concept design is that the value of $ß_2$ is 0, which means that the higher part of the body of the kettle is represented with a straight line. A new design space can be defined that maintains this characteristic. That is, this characteristic is now a requirement for the next generation of concept designs. In order to do that, the pointer $ß_2$ (the square) in the second slider is dragged to the far left, where the value is 0 (Figure 7.22). Thus, because the range of values for $ß_2$ is 0, the straight line in the higher part of the body of the kettle will be kept in all the designs in the new design space (Ds 5).

In addition, more requirements can be introduced into the design space. For example, the designer may want to consider outlines with points of discontinuities – the connection between arcs is not tangential. To do this, the pointer Pd (the circle) in the second slider is dragged to the right. In this example, the range of values for Pd is from 0 to 65 degrees. As pointed out earlier, the value given by the position of the pointer is not meant to give consistency in describing design characteristics.

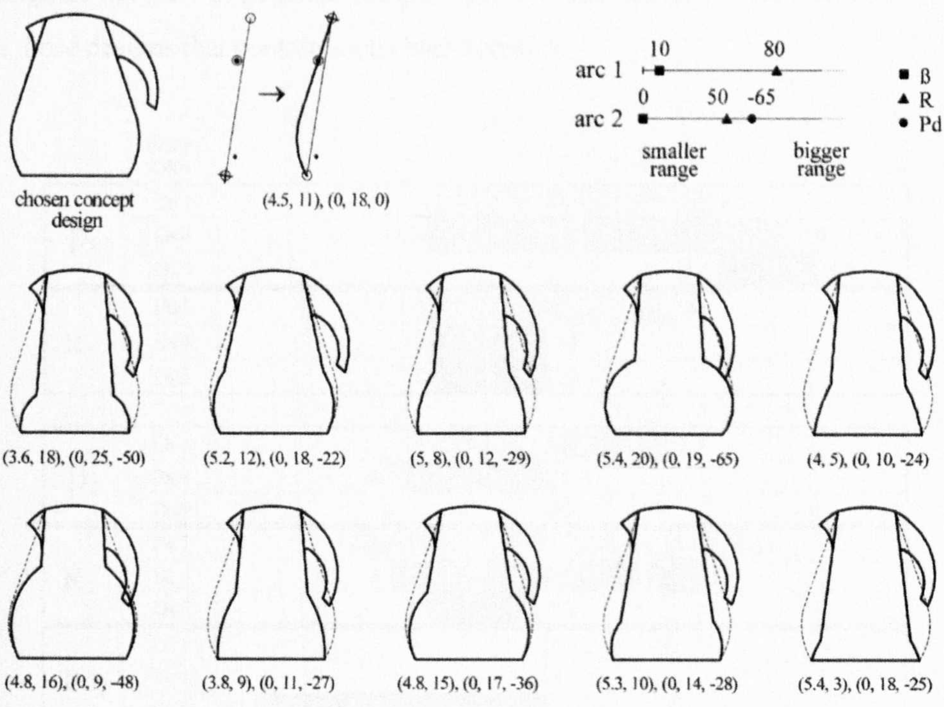


Figure 7.22. Design family 5

A particular value can be sensitive in one type of outline and imperceptible in another type of outline. Dragging the slider to the left will decrease variation while dragging it to the right will increase it. This is sufficient for the intended purpose of this research, because giving more or less variability to a value allows designers to move closer or not to a particular design requirement. Figure 7.22 shows a design family that the outlines contain a point of discontinuity and the higher part of the body of the kettle is a straight line.

Table 7.2 compares the ranges of values (ß, R, and Pd) between the initial design space (Ds 1), Ds 4 and Ds 5. The difference from Table 7.1 is that the ranges of values are taken from different concept designs instead of the initial concept design. For example, the central value for $ß_1$ in Ds 1 is 1, in Ds 4 is 1.9, and Ds 5 is 4.5. As a consequence, it is possible to define displaced design spaces that contain designs not included in previous design spaces and also exclude designs included in previous design spaces. Thus, displaced design spaces assist designers not only to generate designs with new characteristics but also focus only on those designs that contain such characteristics.

	design space			
β_1	Ds 1	-1.5	1	3.5
	Ds 4	-0.8	1.9	4.6
	Ds 5	3.6	4.5	5.4
R_1	Ds 1	0	20	40
	Ds 4	2	11	20
	Ds 5	2	11	20
β_2	Ds 1	-1	0.6	2.3
	Ds 4	-1.7	-0.7	0.3
	Ds 5	0		
R_2	Ds 1	0	30	60
	Ds 4	6	31	56
	Ds 5	9	18	27
Pd_2	Ds 1	0		
	Ds 4	0		
	Ds 5	-65		0

Table 7.2. Range of values for each parameter in design spaces Ds 1, Ds 4, and Ds 5

Figure 7.23 illustrates a schematic representation of these three design spaces, which clearly shows that Ds 4 and Ds 5 are displaced design spaces from Ds 1. It shows that Ds 4 overlaps with Ds 1, and Ds 5 is a detached design space from Ds 1, but overlaps with Ds 4. It also shows that Ds 4 does not include the initial concept design and Ds 5 does not include the first chosen concept design. The ranges of values defined in each parameter make it possible to graphically represent design spaces. The sequence of design spaces display the footprints left by a designer during the exploration process. This provides a useful means to record and document the progress of an idea, but also provides benefits to designers during the exploration process in the sense that they can see their moves from an abstract level. When developing designs, designers need to engage in a reflective process by reviewing their own paths and to consider new paths that lead to creative designs. According to Gero and Kumar (1993), the 'footprints' in Figure 7.20 denote that the path traced from Ds 1 to Ds 3 is less active and creative than the path traced from Ds 1 to Ds 5 (Figure 7.23).

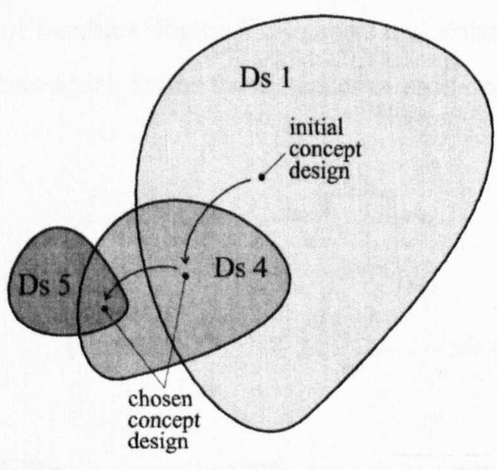


Figure 7.23. Schematic representation of design space 1, 4, and 5

These examples show that outline transformations can generate design families of different ranges of variation between designs; however, there is another approach often used in design to generate design families. The next section examines how design families can be generated via structure transformations.

These two approaches – outline and structure transformations – are here examined separately but in practice they normally operate simultaneously.

7.4.2 Generating design families via structure transformations

New design spaces can also be defined by applying transformations to the structure of the concept design according to requirements. The structure can be transformed in many different ways. Chapter 5 has presented various types of rules to transform defined structures in a formal manner (e.g. relation rules and structural rules). For simplicity, this section focuses on transformations in the diagram of elements which forms part of the structure. Figure 5.15 in Chapter 5 shows two examples of transforming the diagram of elements; however, how the diagram can automatically generate a design family has not been provided. There are many formal ways that are possible by which to transform the diagram of elements whilst generating a design family. One possibility is by giving a range of values to parameters, but different approaches can be used – Chapter 8 will show a more visual way to transform the diagram of elements where there is no need to express parameters in terms of numbers. Figure 7.24 shows a rule that gives parameters to the diagram of elements which define the distances of each decomposition line.

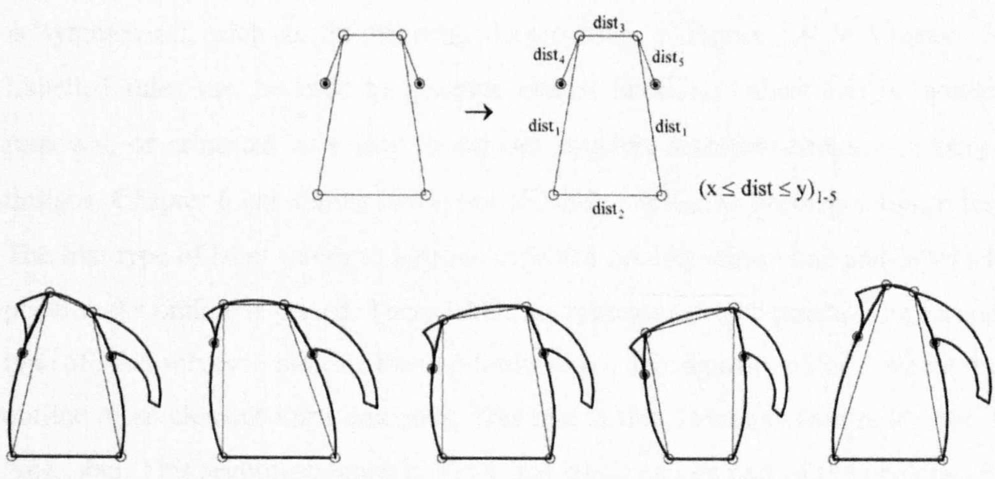


Figure 7.24. Parameters to transform the diagram of elements

Each parameter has a minimum and maximum value. The computer randomly chose a value – within the defined range – for each decomposition line resulting in a variety of diagram of elements. Such transformations generate a design family. Figure 7.24 shows five examples.

As it has been shown in Chapter 5, another way to transform the structure of a concept design is by altering the labels attached to decomposition rules. The labels – here described with points – normally constrain the applicability of the rule (however, as it will be shown below, some labels can expand the applicability of rules). This means that, in general, if the label of a decomposition rule is removed, the rule can generate more designs than those with the label. Labels force the rules to be applied in certain ways, and the position of the label in the rule can change the way the rule is applied. The concept of labels in rules has already been introduced in Chapter 4; this section examines how labels can be used in decomposition rules to transform design spaces.

In most cases, when describing an initial concept design labels are needed to guarantee that rules are applied in the desired place and position. Labels are not required when the outline is applied to both sides of the decomposition line and it is symmetrical, such as the triquetra decomposed in Figure 5.9 in Chapter 5. Labelled rules can be used to generate design families. Labels can be added, removed, or relocated as a way to explore structure transformations of concept designs. Chapter 6 has shown two types of labels applied to decomposition rules. The first type of label serves to indicate in which decomposition line and in which position the outline is placed. These labels are represented with points. The second type of label serves to indicate the two limits of the decomposition line – where the outline of an element starts and ends. This means that decomposition points are a type label. This section attempts to show that labels can be part of the exploration process.

The first type of label examined here is represented with points attached to decomposition lines. They can indicate where and how the outline has to be placed on the decomposition line. Thus, these labels have two functions, (i) differentiate one decomposition line from another, and (ii) the position of the outline on the decomposition line. For simplicity, an abstract shape is used to illustrate how labels attached to decomposition lines generate design families. For example, the decomposition rules in Figure 7.25a can be applied to the diagram of elements in only one way, which generates one design. If the labels are relocated as shown in Figure 7.25b, the design space is expanded because each decomposition rule can be applied in more than one way.

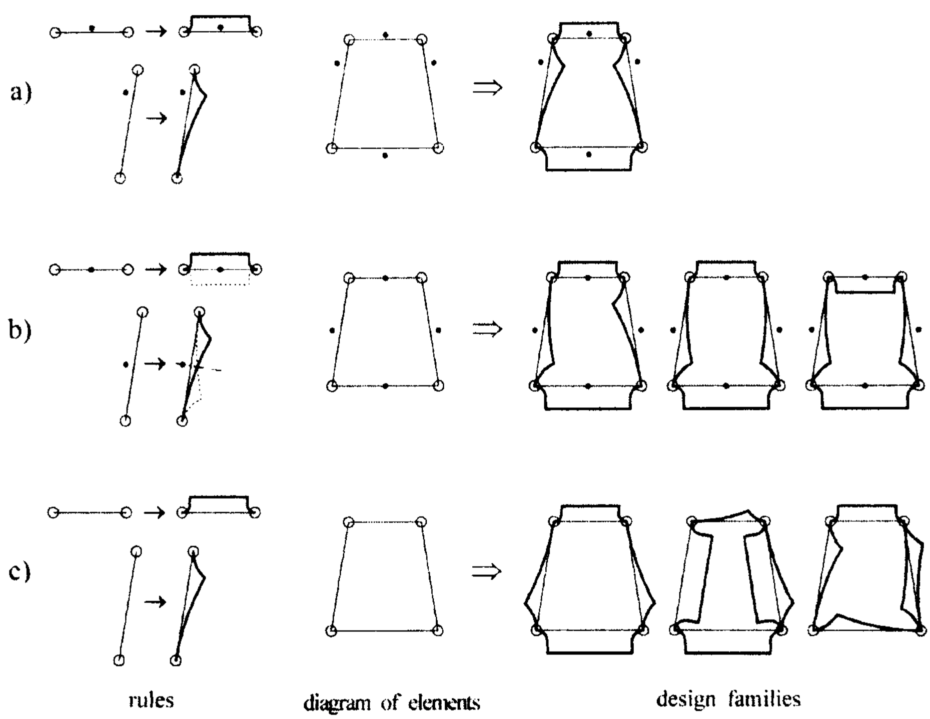


Figure 7.25. Different arrangement of labels generate different design families

Observe that one decomposition rule can be applied to both sides of the decomposition line and the other decomposition rule can be applied in different positions because its outline is asymmetrical. These descriptions generate a design family. If the labels are removed as shown in Figure 7.25c, the design space is expanded again. Each decomposition rule can now be applied to any decomposition line in any position, and also two rules can be applied in one decomposition line – one to each side. This design space contains a vast variety of designs including the design space defined in Figure 7.25a and Figure 7.25b.

The process of developing new ideas is in general very complex, and designers use several different approaches to come up with creative ideas. One of these approaches involves exploring possible combinations and relationships between elements. That is, the elements of a design are kept and only their spatial positions are transformed in order to obtain new designs. This is what labels can do. Labels provide a means for arranging elements of designs according to requirements. Pictorial representations of each different combination form a design family which will display more or less variation between designs depending on requirements. For example, the design family in Figure 7.25b displays less variation than the design family in Figure 7.25c because the design requirements – described through labels – are more restrictive.

Every time that a label of a particular design is added, removed, or relocated, a new design space is defined. The new design space can be expanded, contracted, or displaced. Figure 7.26 illustrates these three relationships between design spaces. Note that a displaced design space can overlap or be detached to the initial design space. The rule in Figure 7.26a removes the labels from the diagram of elements and also from rule x and rule z. As a consequence, the generative process is less constrained and the design space is expanded – from Ds 1 to Ds 2. Ds 1 is defined by the labelled descriptions (the descriptions are the diagram of elements and rules) and Ds 2 by the unlabelled descriptions. If the rule adds labels to the unlabelled descriptions, as shown in Figure 7.26b, the design space is contracted. Altering the arrangement of labels can define new displaced design spaces; the rule in Figure 7.26c defines an overlapped design space and in Figure 7.26d defines a new design space that is detached to Ds 1.

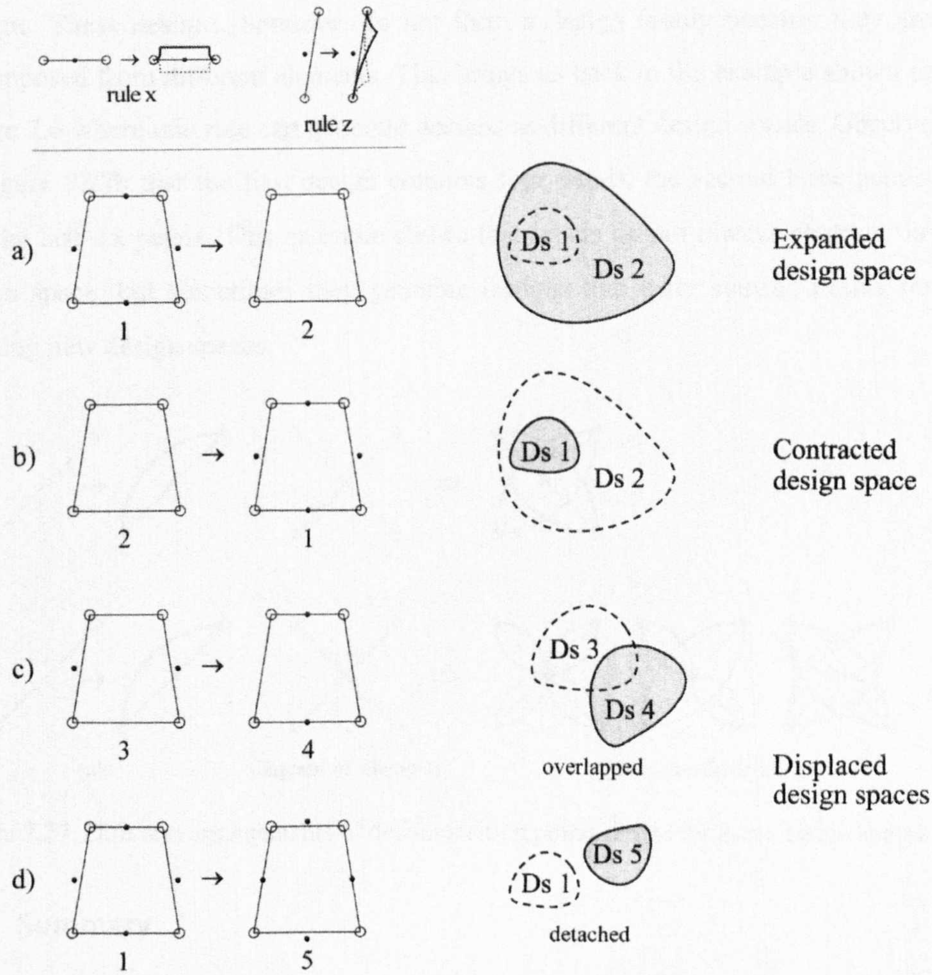


Figure 7.26. Four possible relations between design spaces that can be achieved by altering the labels in shape descriptions

The second type of label examined here is represented with (empty) points, called decomposition points, which are placed at the limits of each decomposition line. In order to illustrate this, an abstract shape is used that the diagram of elements is composed of two crossed decomposition lines. Figure 7.27a shows a decomposition rule that is applied to a diagram of elements to generate two crossed petals. These descriptions can only generate one design, but adding new decomposition points to the diagram of elements means it can generate a variety of designs. In Figure 7.27b a new decomposition point has been added at the intersection point in the diagram of elements. As a consequence, the decomposition rule can be applied in several different ways, which can generate a variety of designs. These designs, however, do not form a design family because they are decomposed from different elements. This brings us back to the example shown in Figure 7.6 where one rule can generate designs in different design spaces. Observe in Figure 7.27b that the first design contains four petals, the second three petals, and the last six petals. This example shows that labels do not always contract the design space, but sometimes they generate designs that offer starting points for defining new design spaces.

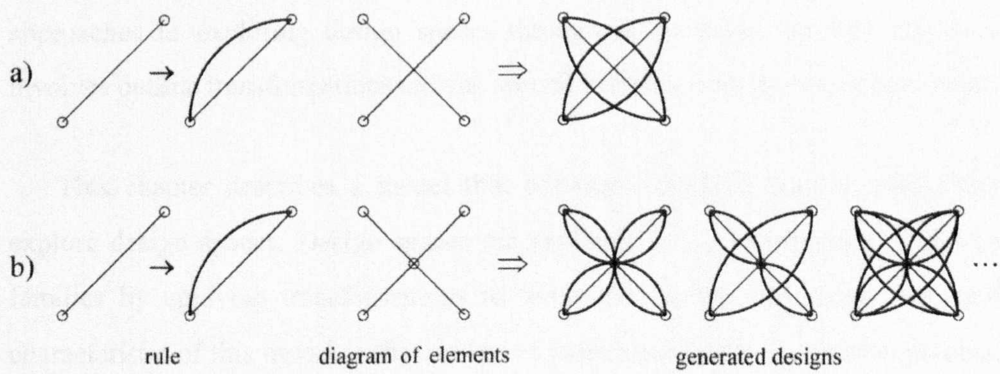


Figure 7.27. Different arrangements of decomposition points define different design spaces

7.5 Summary

The main concern of this chapter is to demonstrate that the model presented in Chapter 5 provides a means to explicitly define and interactively explore design spaces. Woodbury and Burrow (2006) claim that explicit design spaces are important to encode designers' moves which can then be reused. Shape grammars are one of the most common approaches for defining explicit design spaces through a set of rules. They have been frequently used to define design spaces as a means to capture aspects of particular styles and brands. Shape grammar implementations, however, are limited to fixed outlines – straight lines in particular – or fixed structures. In contrast, the work presented in this chapter shows that design spaces are defined as the design process advances. Hence, unlike current shape grammar implementations (at least those that are meant to be used in product design) which explore fixed design spaces, a model is proposed here for exploring while defining design spaces.

The design process, especially in the early stages, involves exploration of different design spaces in addition to focusing on fixed design spaces. This is crucial in creative thinking process (Gero and Kumar 1993). In order to explore new design spaces it is necessary to define new design requirements and/or redefine the existing ones. This chapter describes two different and common approaches to exploring design spaces through shape rules: the first approach involves outline transformations and the second involves structure transformations.

This chapter describes a model that provides a flexible way to define and explore design spaces. Design spaces are explored through generation of design families by applying transformations to the outline and/or structure. The main characteristic of this model is that designers participate in the exploration process. In order to make the process simpler and more dynamic designers normally operate with the same type of parameters, namely ß, R, and Pd. The purpose of this research is not to cover the whole design process, but only the stages where designers explore variations of potential concepts. This model could assist designers in obtaining variations of design concepts quickly. The goal of this work is to give insights on how shape grammars could support exploration of product designs. It has been shown how design families are generated in a hierarchical process of progressive refinement according to designers' requirements. Each generated design family can be understood as a footprint in the design process that makes it possible to examine and explicitly describe designers' steps towards the final design. Such footprints provide designers with a means to reflect on their paths in ways that encourage them to explore new paths.

Chapter 8

Designing with rules and pictorial representations

Overview

This chapter will examine the relationship between the formal mechanisms of decomposition, transformation of shapes proposed in Chapters 5, 6, and 7 and the three processes – reinterpretation, emergence, and abstraction – examined in Chapters 2, 3, and 4. These earlier chapters examined how these processes are used by designers in developing their pictorial representations. The later chapters, using these processes as a starting point, investigated some possible generative mechanisms for developing pictorial representations. The purpose of this chapter is to show that these generative mechanisms are consistent with the processes. Consistency, here means that the generative mechanisms can yield the kinds of development observed in designers' pictorial representations.

The relationship between processes and mechanisms is discussed in two stages. First, the sequences of exploratory sketches that were analysed in Chapter 3 in terms of the three processes – reinterpretation, emergence, and abstraction – are examined in terms of the generative mechanisms – decomposition and transformation. Second, the generative mechanisms are applied to an 'abstract' design shape. The development of the shape through these mechanisms provides a preliminary demonstration that the mechanisms yield types of shape exploration consistent with what takes place in practice whilst being more systematic and extensive. They thus have the potential incorporation in computational tools for product designers as an aid to concept exploration.

8.1 Introduction

Chapter 2 focussed on three cognitive processes that seem to be crucial in product design exploration. The processes of reinterpretation, emergence, and abstraction and the role in design representations appear to be central to design progression from ideas to designs. Chapter 3 built on this and proposed that the generation of creative concept designs resulted in sequences of related sketches that collectively form design families. Figure 8.1 illustrates this in a diagram. The left-hand side of the diagram indicates that the generation of informal design families – often exploiting freehand sketches – involves the use of these three cognitive strategies. At the same time, cognitive processes may be influenced by perception of design families.

After an examination of formal systems for design exploration, with emphasis on shape grammars, a model has been generated in which depicted designs are explored through two generative mechanisms; shape decomposition and shape transformation. These mechanisms are formally described as shape rules. The application of these mechanisms, to an initial concept design, leads to the generation of a formal design family, as indicated in the right-hand side of the diagram in Figure 8.1. Similar to design practice, the formal mechanisms and design families can create dynamic feedback loops in which rules and pictorial representations interact one upon another.

This Chapter discusses issues concerning the validation of this model. It compares the relationship between formal design families and informal design families. Unlike most formal models in the literature of shape grammars, which aim to capture features of existing styles or brands, this model does not intend to explain any particular historical outcome. Rather, it aims to provide a tool to help explore new designs as well as new styles and brands. The model can be validated in two ways: analytically and empirically. The analytical validation involves comparing the proposed mechanisms of decomposition and transformation against the three examined cognitive processes. The empirical validation involves duplicating sequences of sketches from informal design families via the formal model. Although more has to be done to obtain a complete validation of the model, the initial results indicate the ability of the model to generate formal design families consistently with cognitive processes. The generative mechanisms may provide significant benefits for the development of computational systems to assist product designers in the early stage of design exploration.

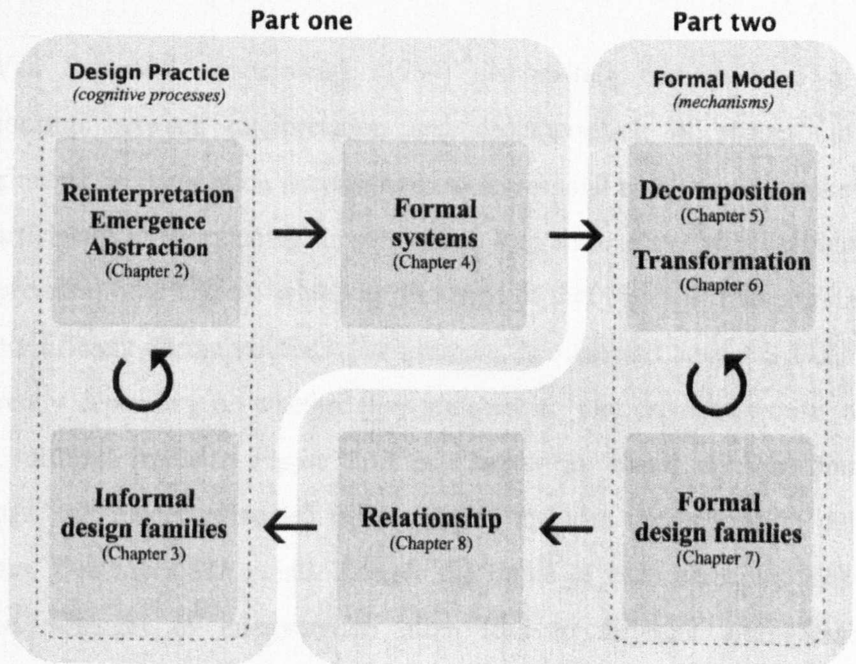


Figure 8.1. Summary diagram of the thesis

8.2 The relationship between formal and informal exploration

This section presents an analytical validation of the model by contrasting the mechanisms of shape decomposition (section 8.2.1) and shape transformation (section 8.2.2), with the processes of reinterpretation, emergence, and abstraction.

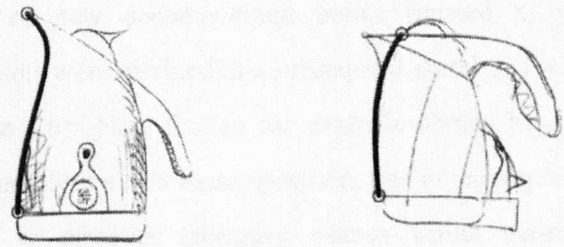
The subsequent section (section 8.2.3) discusses how the formal model can duplicate a sequence of sketches generated by a participant. This validation could be regarded as semi-empirical, existing somewhere between empirical and analytical validation, because the duplication is not performed by the participant who produced the sketches, but by the author of this thesis. A purely empirical validation proved beyond the scope and resources of this thesis and is regarded as further work.

8.2.1 Decomposition

The model presented in Chapter 5 provides a number of descriptions to decompose shapes into elements. This section examines the relationships between these formal decompositions and the processes of reinterpretation, emergence, and abstraction.

Van Sommers' experiments (1984) demonstrate that there is a strong relationship between interpretation and decomposition of shapes. In these experiments decomposition is considered to correspond with the pen strokes made by participants in reproducing simple shapes. Van Sommers shows that changes of interpretation of a shape – which in the terms of this thesis is 'reinterpretation' – lead to different decompositions. For example, two crossed lines are decomposed differently depending on whether they are seen as 'two crossed swords' or 'two mice sniffing' (refer to Figure 2.13 in Chapter 2). Based on Van Sommers' findings, the model presented in this thesis includes decomposition points to outlines. Decomposition points indicate the limits of each perceived part of an outline. Changes of interpretation often lead to different arrangements of decomposition points. Figure 8.2 illustrates a sequence of two sketches produced by a participant (as discussed in Chapter 3).

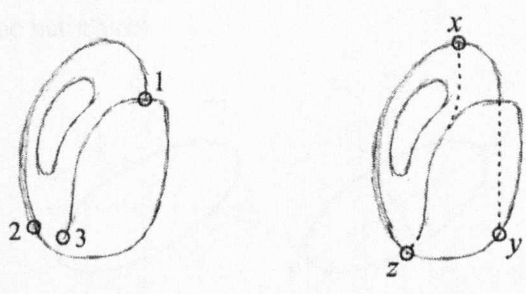
Two decomposition points on each sketch correspond to the strokes (shown in thick line) traced by the participant. Although in essence these two sketches are topologically similar, the decomposition points indicate that the participant interpreted Figure 8.2a and Figure 8.2b differently. This example illustrates a relationship between decomposition points and interpretation of a shape. Figure 8.2 suggests that, from the participant's perception, these sketches belong to two different design spaces.



a) b)

Figure 8.2. Decomposition points indicate a participant's interpretation of the sketch

In general, the thesis has considered emergent shapes as composed of elements that were not previously considered as elements. Discovering emergent shapes corresponds to new elements and leads to new arrangements of decomposition points. For example, the strokes traced by the participant to produce the outer outline of the sketch shown in Figure 8.3a suggests three decomposition points (numbered 1, 2, and 3).



a) b)

Figure 8.3. (a) Decomposition points introduced according to strokes, (b) discovery of emergent elements leads to the introduction of new decomposition points

The strokes traced to produce the subsequent sketch (illustrated in Figure 3.3 in Chapter 3) suggests that this participant discovered an emergent shape through a transformational process (Soufi and Edmonds 1996).

According to Soufi and Edmonds, emergent shapes associated with a transformational process can arise as a result of extending the outlines used to depict a shape. Based on this, Figure 8.3b shows a possible action performed by one participant, which extends outlines to meet other outlines. Such action leads to the introduction of new decomposition points (named x, y, and z). These decomposition points were retained in a subsequent sketch (as will be shown in the subsequent Figure 8.6) Note that in the example shown here, the discovery of emergent shapes involves a new decomposition, that is reinterpretation; however, it is also possible to discover emergent shapes whilst maintaining the same decomposition and section 8.3 will present an example.

As discussed in Chapter 2, shapes have two properties; outline and structure (Arnheim 1974). While outlines are graphically represented in sketches, structures are not explicitly given. In general, outlines and structures are 'seen' as different levels of abstraction. If structures are represented, they are often established by the main axes of the shape. Consider the sketch shown in Figure 8.4a, where the character of the outline is, to some extent, given by the perceived structure. Now compare the structures given in Figure 8.4b and Figure 8.4c, where they differ in the orientation of the main axes.

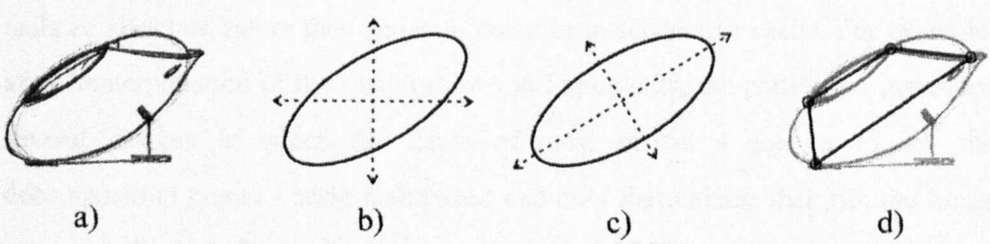


Figure 8.4. (a) A concept design, (b) perception of a static structure, (c) perception of a dynamic structure, and (d) definition of a dynamic diagram of elements

The ellipse in Figure 8.4b with vertical and horizontal axes has a more static character than the ellipse in Figure 8.4c which has an obliquely oriented structure (similar examples are illustrated in Arnheim 1966). In Chapter 2 it was argued that structures can be crucial to an understanding of shape transformations since they provide designers with a frame of reference (Tversky 2001). In the model presented in this thesis the structure is defined by decomposition lines that join decomposition points to form a diagram of elements (Figure 8.4d).

The diagram of elements shown in Figure 8.4d was defined according to the strokes traced by the participant to produce a sequence of similar designs. Note that the kind of diagram of elements shown in Figure 8.4d is not meant to represent lines that designers see in shapes but it is a construct to indicate designers' interpretations.

8.2.2 Transformation

This section examines the relationships between formal transformations and the three processes discussed in Part One – reinterpretation, emergence, and abstraction. It is proposed that the mechanisms to transform shapes are comparable with the kind of transformations applied in freehand sketches.

The analysis of the sketches produced in the empirical study shows that, in general, after (re)interpretation of a design, participants generate sequences of sketches that preserve the same decomposition. This was also observed by Goldschmidt (1994) who points out that designers rarely produce single and isolated sketches, rather they generate sketches in successive spells. For example, after reinterpretation of the sketch shown in Figure 8.2a, the participant generated several designs in which the limits of most strokes – that is to say the decomposition points – were maintained and only the outlines that join the limits were transformed. Piecewise line-rules presented in Chapter 6 show that curved outlines can be transformed through a few parameters which assist the generation of design families. Chapter 7 associates these parameters with sliders that are used to allow more or less variability between outlines. Figure 8.5 shows three sketches with decomposition points in the same place. It also shows the values of the parameters β, R, and Pd for each sketch. The position of the sliders is determined by the minimum and maximum values for each parameter within the three outlines.

The ranges of values defined in the sliders generate similar outlines that were used by the participant to produce other sketches of the same concept design, but also can generate new outlines that are consistent with the design family.

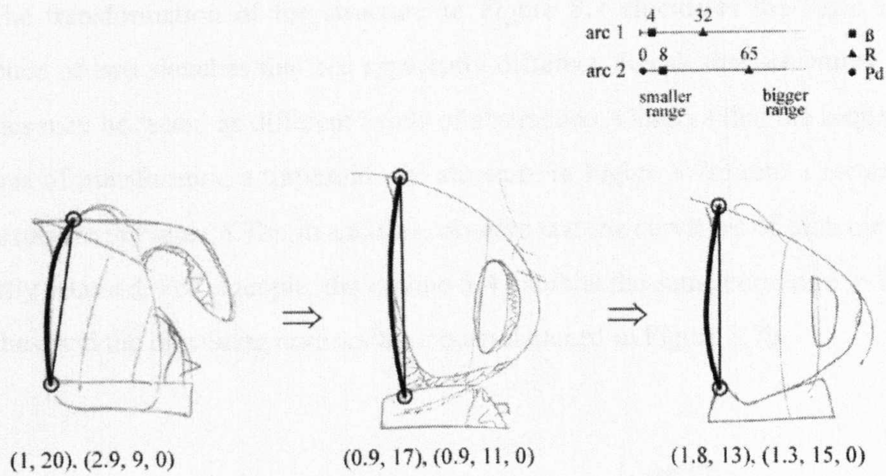


Figure 8.5. Outline transformation

According to the study presented in Chapter 3, the most frequent type of emergence is based on transformational processes. That is, emergent shapes are visually suggested by outlines but not graphically represented. Figure 8.6a shows the position of decomposition points (named x, y, and z) according to a possible emergent shape based on a transformational process.

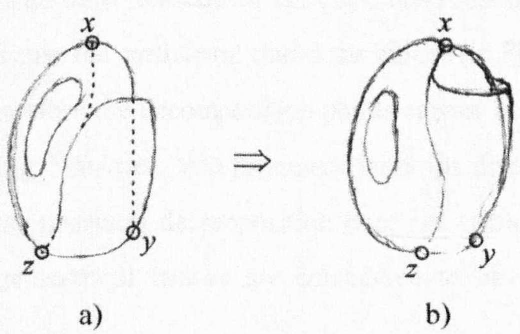


Figure 8.6. New introduced decomposition points are kept after shape transformation

Figure 8.6b demonstrates that, in the subsequent sketch produced by the participant, the decomposition points x, y, and z were maintained. Note that the decomposition points in Figure 8.6b are positioned according to the strokes traced by the participant. This example indicates that decomposition points correspond with designers' perception.

The transformation of the structure in Figure 8.7 elucidates the logic in a sequence of two sketches that are apparently different. Recall that structures and outlines may be 'seen' as different levels of abstraction. Observe that the sequence consists of transforming a trapezoid (the structure in Figure 8.7a) into a rectangle (the structure in Figure 8.7b). In addition, observe that the curvature of each outline is partly retained. For example, the outline 3-4 exhibits the same curvature in both sketches, and the remaining outlines have been flattened in Figure 8.7b.

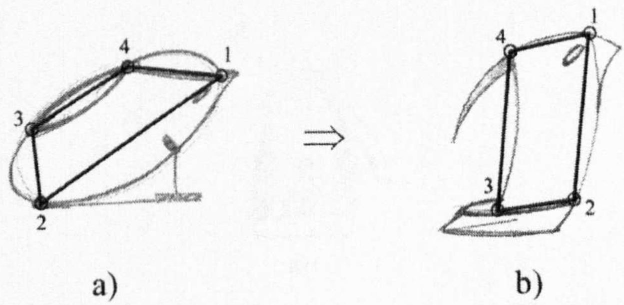


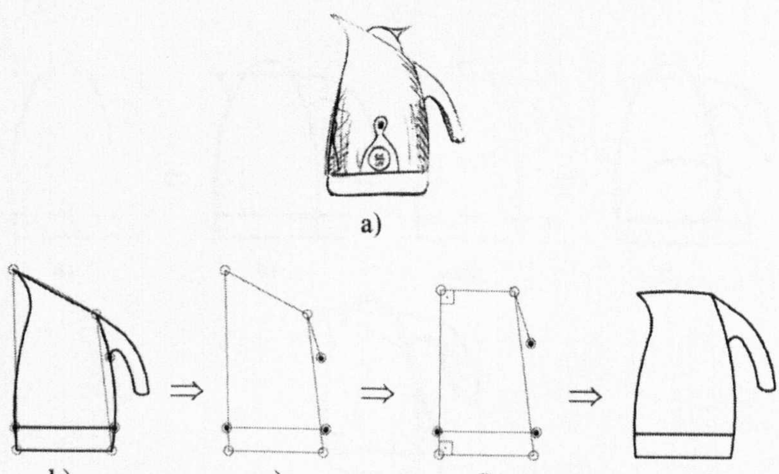
Figure 8.7. Transformation of the diagram of elements

Although such a structure offers a logical connection between these two sketches as well as with other subsequent sketches, this remains as a hypothesis to be tested. This is because the participant traced the ellipse (in Figure 8.7a) with one single stroke and therefore the decomposition points cannot be identified from the strokes in the drawing. However, Van Sommers' work (as discussed in Chapter 2) suggests that in some instances decomposition does not correspond with strokes, particularly when geometrical factors are considered to be more relevant than semantic factors.

8.2.3 Formal design families

It is proposed that assigning particular structures to designs assists generation of design families. Structures may ensure that computationally generated designs are consistent with the designer's perceptual processes. They are defined according to designer's interpretations and intentions. Consider for example the sketch in Figure 8.8a, which has been taken from the empirical study presented in Chapter 3.

The design can be decomposed by assigning decomposition points and decomposition lines as shown in Figure 8.8b. The added lines take the form of a structure (Figure 8.8c), which can be transformed according to aesthetic preferences. A rule (not illustrated here) that arranges two connected lines into a right angle generates the structure shown in Figure 8.8d. This is just one possibility from a range of configurations, as illustrated in section 7.4.2 in Chapter 7. Figure 8.8e shows the outlines attached to the modified structure.



a)

b) c) d) e)

Figure 8.8. Defining and transforming the diagram of elements

New elements of detail may be added to this design as shown in Figure 8.9a. If the introduction of these elements is defined in terms of shape rules they may generate additional designs as previously illustrated. Once the elements are in place an inspection of the design may suggest new interpretations. Figure 8.9b and Figure 8.9c show a possible structure defined according to a new reinterpretation. Design alternatives can be explored by transforming the outlines defined by the structure. Figure 8.9d and Figure 8.9e show two examples.

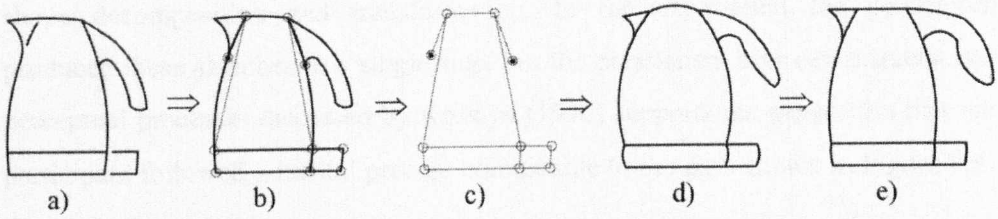


Figure 8.9. Reinterpretation of the design in Figure 8.8 and transformations of outlines

With the purpose of inserting a lid in the kettle a new rule could be defined. For example, two symmetrical curves are found (shown in thick line in Figure 8.10a) and they are joined with an arc from their end points as shown in Figure 8.10b. However, this rule can generate unexpected designs through emergent features as show Figure 8.10c and Figure 8.10d. Observe the similarities between the last design and the sketch in Figure 8.10e taken from the empirical study.

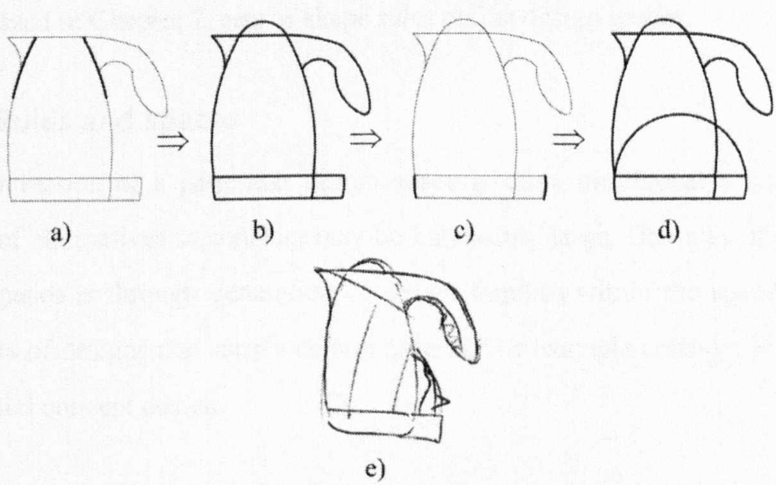


Figure 8.10. Insertion and emergence of new features

This example attempts to show that sequences of designs, at least in convergent thinking, can be traced in a systematic and logical way. Here a path of development has been traced that formalizes the sequence of modifying one sketch (Figure 8.8a) into another (Figure 8.10e). This path has been constructed in two stages. First the design developments in the path are identified with the three processes of reinterpretation, emergence, and abstraction as examined in the empirical study. Second each of these processes is expressed using the generative mechanisms of shape decomposition and transformation. In the experiment the participant produced these sketches in a single step, but the parallelism between imagery and perceptual processes discussed by Kosslyn (1990) supports the suggestion that the participant followed a mental process comparable to the path shown in Figure 8.8-Figure 8.10.

8.3 A formal process for exploring designs

In the exploration process the transformation from one concept design into another can be in myriad different ways. The generative mechanisms of decomposition and transformations proposed in Chapters 5 and 6 have been expressed in terms of shape rules. Shape rules provide a means to decompose shapes according to designer's interpretation, and transform them according to designer's requirements. As discussed in Chapter 7, sets of shape rules define design spaces.

8.3.1 Rules and spaces

The examination of a particular design space is often unachievable because the number of alternatives to consider may be impossibly large. One way of exploring design spaces is through generation of design families within the space. That is, sequences of designs that satisfy certain criteria. For example consider Figure 8.11 as an initial concept design.

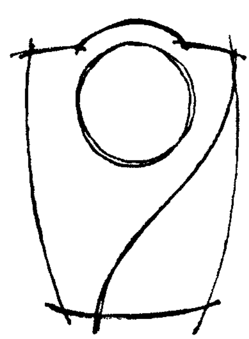


Figure 8.11. Initial concept design

This initial concept design is open to a wide choice of interpretation. Each particular interpretation may direct the exploration process towards particular design alternatives while dismissing other ones. For example, if the circle in the initial concept design is interpreted as a hole (e.g. similar to a hand bag), then designs that contain the circle outside the outer outlines would be not considered unless the circle is reinterpreted, that is to say that the circle is not seen as a hole anymore.

Significant aspects of shape interpretations can be formalized by defining a diagram of elements, which is composed of decomposition points and decomposition lines. The diagram of elements serves to describe the elements perceived in a shape. Chapter 2 has argued that the strokes produced in freehand sketches often correspond with the elements perceived by the designer. Decomposition points are placed on the limits of each perceived element, thus, the start and end points of each stroke can be considered as decomposition points. Decomposition lines can be defined by joining the two limits of each stroke with a straight line. These decomposition lines are supporting shapes that assist the formulation of the shape rules but are not strictly part of the design. If the sketch is drawn directly on a computer (e.g. through an electronic pen and digital tablet-screen) decomposition points and decomposition lines could be automatically defined by the computer in relation to the sequence of strokes used to draw the sketch. Note that some hand-drawing techniques such as production of multi-stroke lines are not considered. In such cases the decomposition points and decomposition lines are not necessarily apparent from the sketch itself, although the designer might identify them after generation of the sketch.

Figure 8.12 shows three different decompositions of the initial concept design. The diagram of elements shown in Figure 8.12a is constructed according to the strokes used to draw the sketch. Note that the circle in the initial concept design is not decomposed by any of the diagram of elements illustrated here. Precisely how the position of the circle can be formalized will be discussed later in this section.

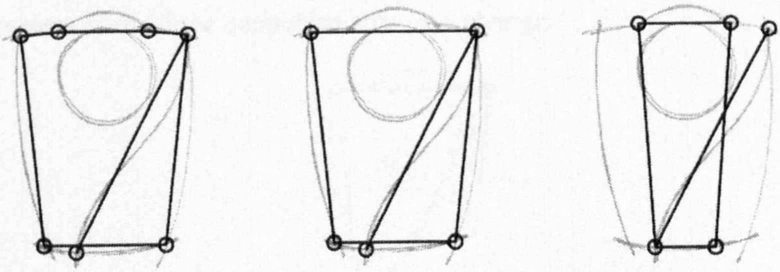


Figure 8.12. Three different decompositions of the initial concept design

Suppose that the initial concept design is decomposed as illustrated in Figure 8.12b. The design is decomposed into five elements and their outlines are defined via piecewise line-rules, that is, each outline is expressed in terms of ß, R, and Pd parameters. These outlines are defined in decomposition rules (Figure 8.13b). Note that rule 1a (figure 8.13b) defines two outlines of the initial concept design and therefore only four decomposition rules are needed. Adjacent to the decomposition lines are labels that ensure that each rule is applied in the required place and in the required position. Observe that a mobile decomposition point – presented in Chapter 6 (section 4.2) – is introduced in rule 4a. This indicates that one limit of the outline is connected to another outline; the outline in rule 2a. Thus rule 4a relies upon rule 2a. Figure 8.13c shows that the application of the rules 1a - 4a to the diagram of elements duplicates the sketch of the initial concept design. The outlines introduced in the diagram of elements are placed in a new layer, namely the design layer, whilst the initial sketch is kept in the contour layer. Note that the contour layer is not illustrated in the right-hand side of Figure 8.13c.

The circle that appears in the initial concept design is here interpreted as a continuous outline which does not have limits. A different type of rule is used to define it. The relationship between the circle and the outer outline may be formalized through the application of another rule (rule x) as illustrated in Figure 8.14. This rule adds a circle to the design whenever three connected arcs – with certain conditions – are found. Note that in order to make rule x applicable during the generation process the left-hand side of the rule should be parametric because the parameters of the three connected arcs may change.

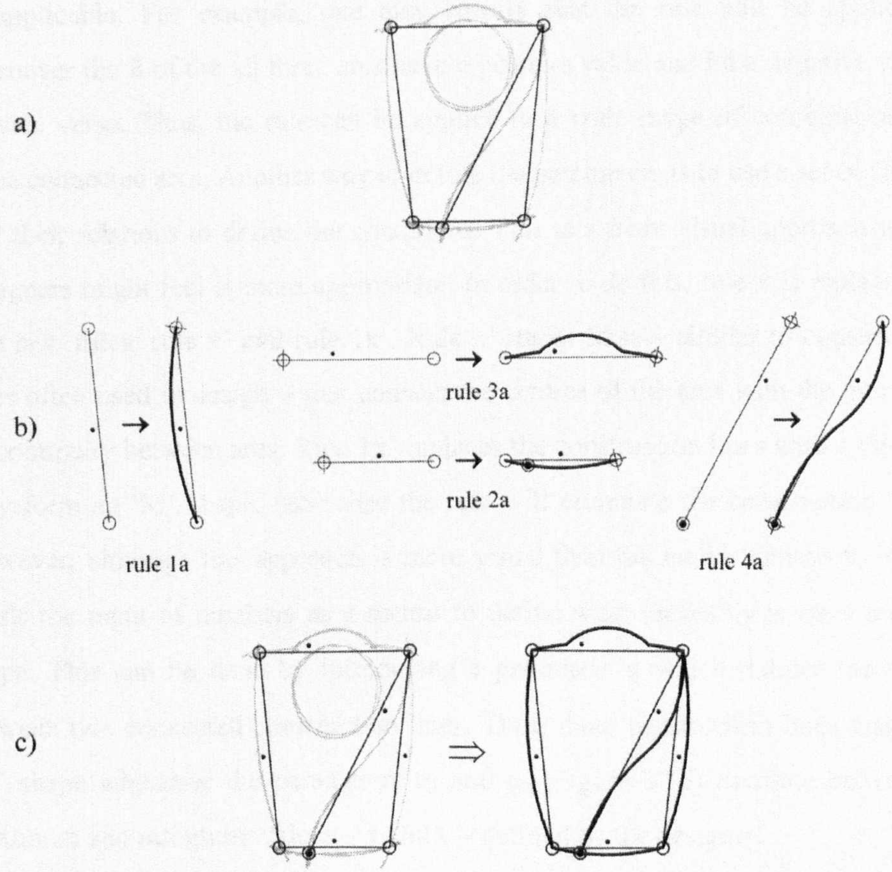


Figure 8.13. (a) Diagram of elements, (b) set of decomposition rules, and (c) the initial concept design is duplicated by application of decomposition rules to the diagram of elements

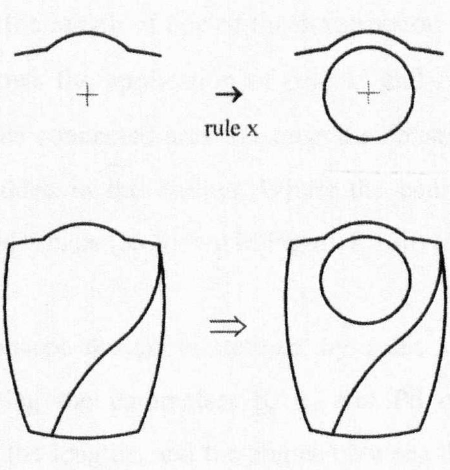


Figure 8.14. Shape rule for inserting a circle

There are several ways to define the parameters of rule x. One possible way is to use the parameters ß and Pd of the three connected arcs to specify when the rule is applicable. For example, one may specify that the rule will be applicable whenever the ß of the all three arcs have a positive value and Pd a negative value, or vice versa. Thus, the rule can be applied to a wide range of combinations of three connected arcs. Another way to define the parameters is to use a set of shapes and their relations to define the conditions. This is a more visual approach which designers might feel is more appropriate. In order to do this, rule x is replaced by two new rules; rule x' and rule 1x'. Rule x' traces lines – similar to construction lines often used in design – that connect the centres of the arcs with the points of discontinuity between arcs. Rule 1x' replaces the construction lines with a circle if they form an 'M' shape, otherwise the rule will eliminate the construction lines. However, although this approach is more visual than the earlier approach, it also needs the input of numbers as a means to define what makes three lines an 'M' shape. This can be done by introducing a parameter α which defines the angle between two connected construction lines. Thus, three construction lines make an 'M' shape whenever the parameters α_1 and α_2 (Figure 8.15) oscillate between a maximum and minimum values – x and y – defined by the designer.

The added circle can also be parameterized. For example, a parameter could define the radius r_2 of the circle that oscillates between a value greater than 0 and smaller than r_1, being r_1 the length of one of the construction lines that goes to the centre. Figure 8.15a shows the application of rule x' and rule 1x' to a random outline composed of three connected arcs. Because the construction lines form an 'M' shape a circle is added to the outline. Where the construction lines in the outline do not form an 'M' shape (as shown in Figure 8.15b) a circle is not added.

Once the initial concept design is defined by rules new designs can be generated by manipulating the parameters β, R, and Pd of the rules, that is, manipulating the radius, the lengths, and the angles between the arcs that compose the outlines as well as other parameters such as the radius of the circle r_2. A sequence of designs is shown in Figure 8.16, here called design family 1.

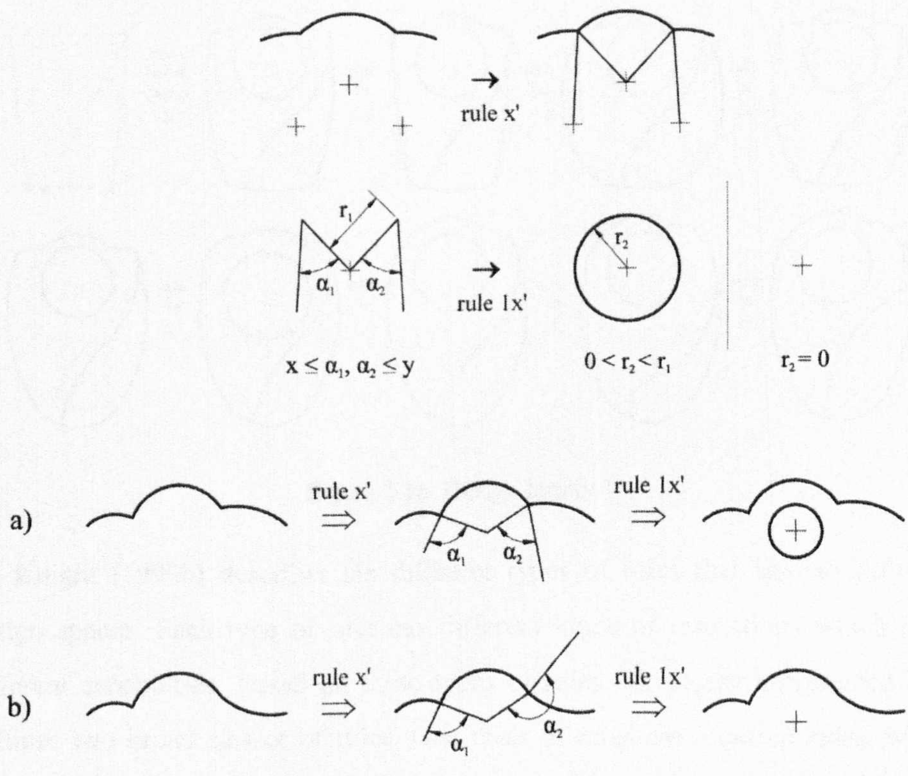


Figure 8.15. Parameters of rule x

The parameters can be modified according to constraints defined by designers. Chapter 6 has shown how constraints can be defined through sliders; however, for simplicity, the sliders and the values of each parameter are not illustrated in this chapter. In order to simplify the process of applying the generative mechanisms the rules are applied one at a time. For example, once the initial concept design has been duplicated by the rules 1a-4a and rule x, the transformation process starts with the application of rule 1a, then rule 2a, and so on. Note that the dashed lines in the figure illustrate the outline that has been transformed by that rule.

Chapter 7 has discussed design families that are generated through rules according to the designers' requirements. Requirements, however, can be more or less significant. A set of rules can define different design spaces depending on which rules must be applied to meet necessary or design requirements and on the sequence in which they are applied.

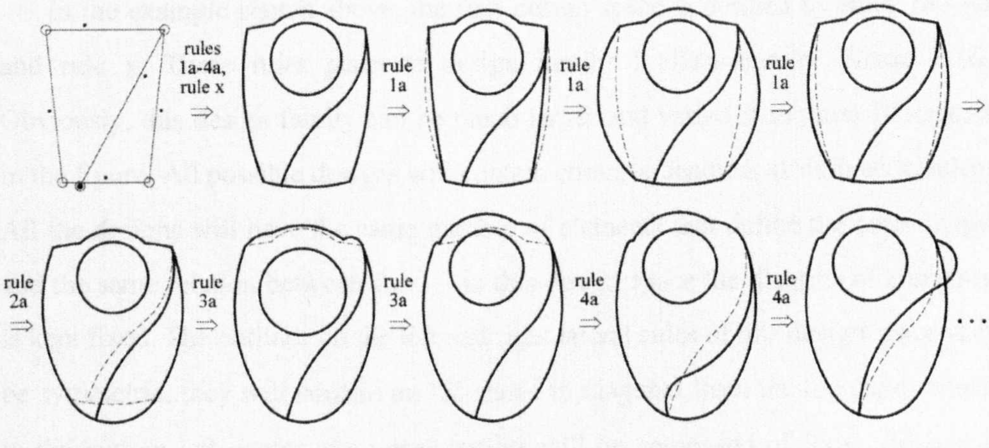


Figure 8.16. Design family 1

Knight (1999b) describes six different types of rules that lead to different design spaces. Each type of rule has different kinds of restrictions which offer different capabilities. Based on these types of rules, the research presented here outlines two broad classes of rules. One class of rules are *required rules*, which means that the rule must be applied whenever an instance of the left-side shape of the rule is found in the design. The other class of rules is defined as *optional rules*, which means that the rule can be either applied or not even when an instance of the left-side shape of the rule is found in the design. In order to distinguish between these two classes of rules they are named differently; required rules are named with a number and a letter (e.g. 1a, 2a, 1b) and optional rules with a letter (e.g. x, x', z).

Thus, the four rules 1a - 4a defined in Figure 8.13 must always be applied to the design, and any design with one or more of these outlines missing is not considered to form part of the defined design space. Rule x', on the other hand, may not be applied even if three connected arcs are found in the design. This means that the construction lines may not be added to the design and as a consequence the circle cannot also be added to the design. Note that in order to avoid obtaining designs with construction lines rule 1x' is a required rule because this rule removes the construction lines.

In the example shown above, the first design space is defined by rules 1a - 4a and rule x. These rules generate design family 1 illustrated in Figure 8.16. Obviously, this design family can be much larger and varied than those illustrated in the figure. All possible designs will contain common features as defined in rules. All the designs will have the same number of elements that define the outer shape and the same relation between them – in this design space the diagram of elements is kept fixed. The outlines on the left and right lateral sides of this design space will be symmetric, they will contain an 'S' shape in diagonal from the top right corner to the bottom left corner, the upper outline will be composed of three connected arcs, and so on. These and other characteristics are requirements that define this design space, which is named Ds 1 (Figure 8.18).

As examined in Chapter 7, it is possible to contract a design space as a means of focussing on particular elements of the concept design. That is, a design space can be contracted by applying a selection of rules. For example, one may want only to explore transformations of outlines to the left and right lateral sides of a design. In this case only rule 1a would be applied. The sketches presented in Chapter 3 suggest that designers often generate sequences of sketches where only one feature is continually transformed whilst other features are maintained. That means that the space of possibilities is contracted. In addition, the contracted design space can also be displaced by considering new types of outlines. Figure 8.17, shows new types of outline defined by a new rule.

The outline in rule 1a, which is composed of one arc, is replaced with an outline composed of two arcs with different signs (rule 1a'). This schema only generates designs with 'wavy' outlines and the initial design space does not contain designs with 'wavy' outlines; Figure 8.17 illustrates four examples. Hence, this schema defines a new design space (called Ds 2) that has been displaced outside the initial design space (Ds 1). This is a detached design space.

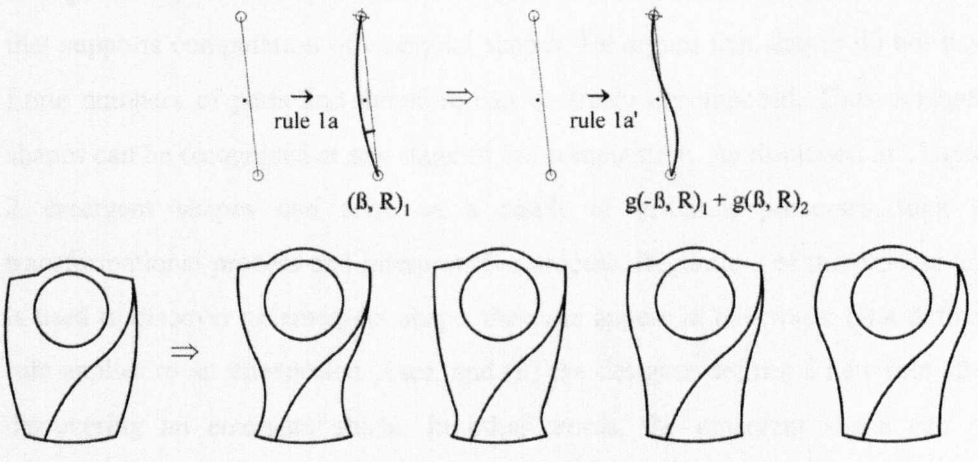


Figure 8.17. Design family generated via application of a schema to decomposition rule

Figure 8.18 shows that any movement between two designs in the design spaces will result in a vertical transformation, even if these two designs belong to detached design spaces such as Ds 1 and Ds 2. They are vertical transformations because all possible designs that can be generated by the rules are composed of the same elements arranged as defines the structure in Figure 8.12b.

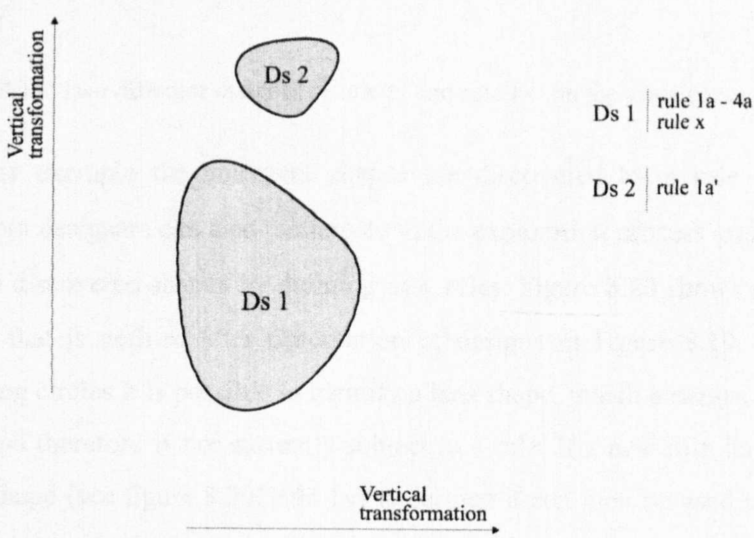


Figure 8.18. The initial design space (Ds 1) and a detached design space (Ds 2). See Figure 8.31 for example of lateral transformation.

8.3.2 Emergence

The empirical study presented in Chapter 3 examined how unexpected shapes emerge during the conceptual design stage. Stiny (1980a) has proposed a method that supports computation of emergent shapes. He argues that shapes do not have finite numbers of parts and therefore can be freely decomposed. Thus emergent shapes can be recognized at any stage of the computation. As discussed in Chapter 2 emergent shapes can arise as a result of different processes such as transformational process and interpretative process. Regardless of the process that is used to discover an emergent shape, they can appear in two ways: (i) a defined rule applies to an unexpected place, and (ii) the designer defines a new rule after discovering an emergent shape. In other words, the emergent shape can be discovered by a rule or by the designer. Figure 8.19 shows that the rule x' discovers an emergent outline composed of three connected arcs – that forms an 'M' shape – which allow rule 1x' to add circles to unexpected places.

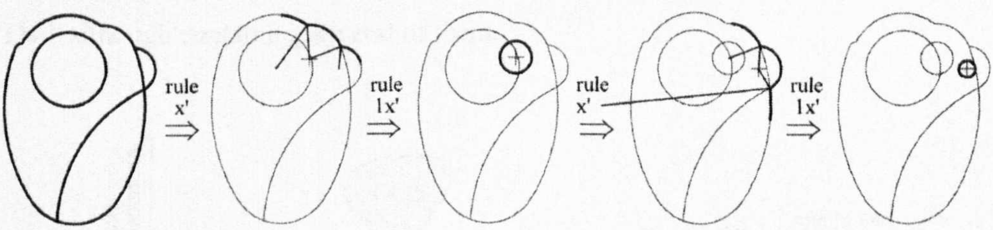


Figure 8.19. Two different matches of rule x' and rule 1x' on the same concept design

In this example the emergent shapes are discovered by a rule previously defined, but designers can also participate in the exploration process and transform their own discovered shapes by defining new rules. Figure 8.20 shows a new rule (rule 1y) that is defined after observation of designs in Figure 8.19. From two overlapping circles it is possible to identify a lens shape, which emerges during the process and therefore is not currently subject to a rule. If a new rule for acting on the lens shape (see figure 8.20, rule 1y) is defined it can then be used to find and transform other emergent lens shapes that may not have been identified by the designer.

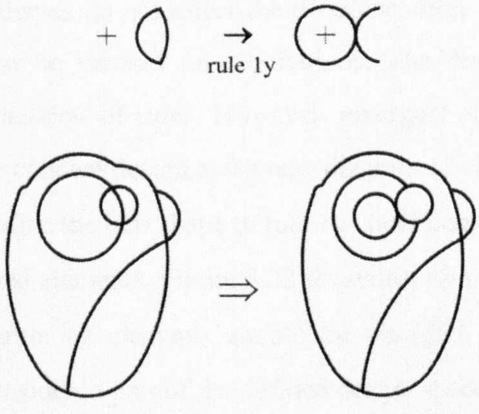


Figure 8.20. Defining a new rule to be applied to an emergent shape

The introduction of rule 1y (figure 8.20) to the set of rules results in a new design space, say Ds 3 (Figure 8.21). Note that the designs in Figure 8.19 do not belong to the design space Ds 3 because the lens shapes – defined as a required rule – have not been replaced by rule 1y. The new design space, Ds 3, which contains designs that were not possible earlier, does not contain all the designs included in Ds 1 although containing several of them.

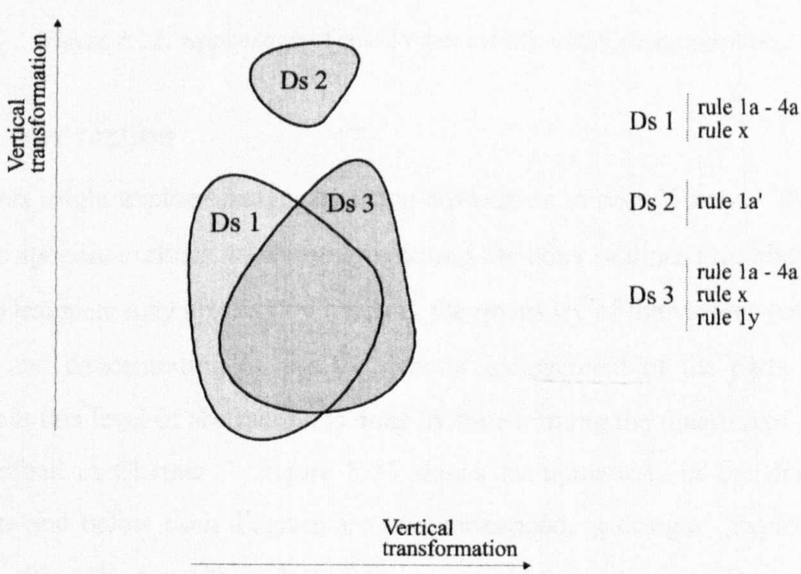
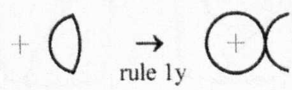


Figure 8.21. Ds 3 overlaps with the initial design space (Ds 1)

These emergent shapes do not affect the decomposition of the concept design and are considered to be vertical transformations. The diagram of elements is maintained after application of rules. However, emergent shapes often lead to a reinterpretation of the concept design and a new diagram of elements. For example, the parameters that define the lens shape in rule 1y could be wide enough to be able to replace some defined elements. Figure 8.22 illustrates two possible examples. In these cases the diagram of elements should be changed. This gives a lateral transformation not considered part of the defined design space, and offering a point of departure to define a new design space.



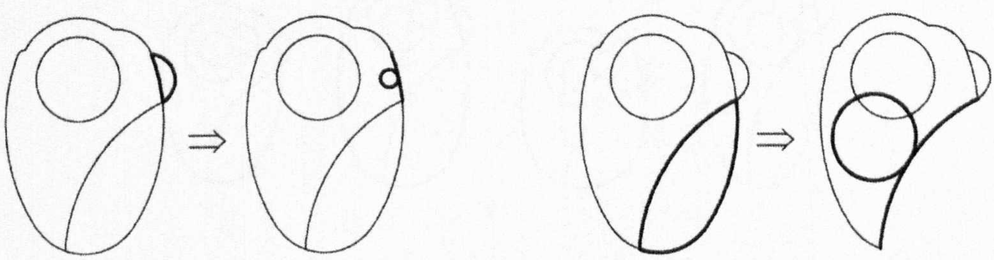


Figure 8.22. Application of rule 1y can modify initial decomposition

8.3.3 Abstraction

Designers might explore designs by using abstraction in several ways. Rules may apply to specific outlines, temporarily ignoring the other outlines (see above figure 8.17). Designers may abstract by ignoring the geometry of the various parts of the outline and concentrating on the the general arrangement of the parts outlines. Change at this level of abstraction is done by transforming the diagram of elements as described in Chapter 7. Figure 8.23 shows manipulations in the diagram of elements and below each diagram are two corresponding designs Exploration of designs not only consists in transforming visible outlines, but also examining hidden structures to find internal coherence in designs. Note that once a promising diagram of elements has been found all previous designs – from Figure 8.16 to

Figure 8.20 – and also potential designs in the design space can be adapted to the transformed diagram of elements.

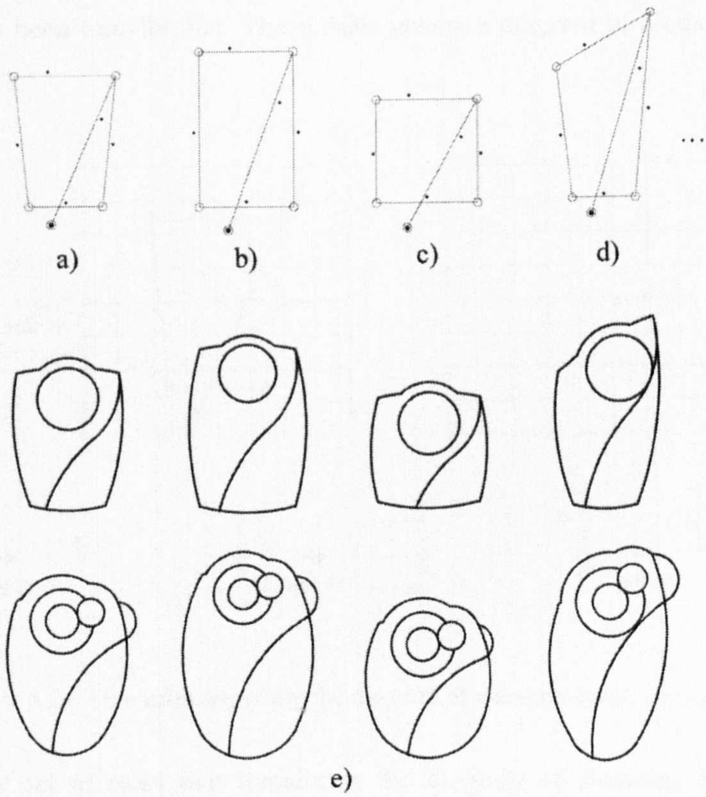


Figure 8.23. (a-d) Transformations of the diagram of elements, (e) outlines attached to diagram of elements form Ds 4

Different strategies can be adopted to transform the diagram of elements. This depends on the designer and establishing a strategy is also part of the creative process. It has been proposed in Chapter 7 that transformations in the diagram of elements can be defined in terms of numbers that give values to parameters. Here a more visual approach is adopted. Instead of using numbers, a grid is used that serves to define a range of possible spatial positions of decomposition points and decomposition lines. Rule 1z in Figure 8.24 adds a grid to the initial diagram of elements. Rule 2z moves a decomposition point to its nearest intersecting point of the grid. Rule 3z moves a decomposition point at an intersecting point to the next intersecting point – this can move the point in four directions. Note that in order to keep control of the transformation process this rule might usefully be limited to two applications per point. Rule 4z reconnects decomposition lines with the moved decomposition point. Finally, rule 5z removes the grid once the diagram of elements has been transformed. These rules generate diagram of elements similar to Figure 8.23.

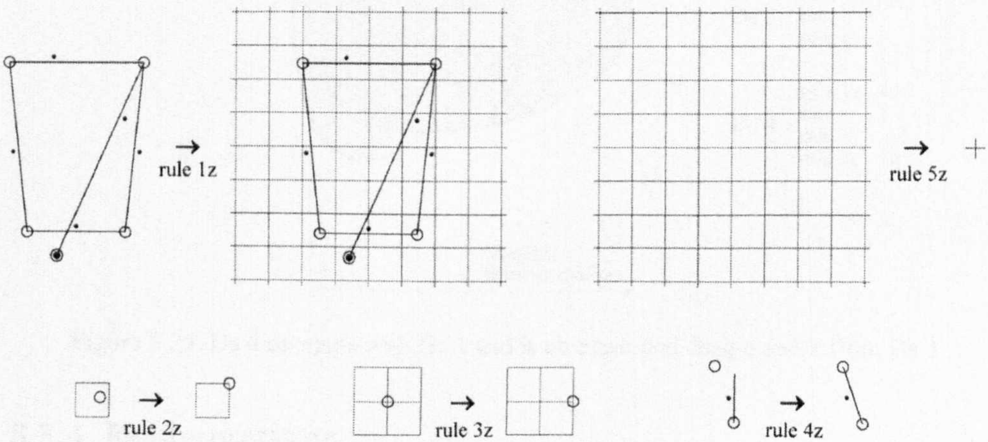


Figure 8.24. Five rules transform the diagram of elements based on a grid

The new set of rules that transforms the diagram of elements expands the design space; in this case Ds 3 is expanded and defines Ds 4. The new design space contains all the designs contained in Ds 3 and also variations in the diagram of elements of these designs. The scope of this extended design space depends on the rules that transform the diagram of elements. Figure 8.24 shows a possible set of rules but different strategies can be adopted.

So far, all the designs that have been illustrated in this chapter (excluding those in Figure 8.22) are vertical transformations of the initial concept design. Here the relationships between decomposition points and decomposition lines defined in Figure 8.13 are maintained during the generation process and the diagram of elements is consistent with the designer's interpretation in the initial concept design.

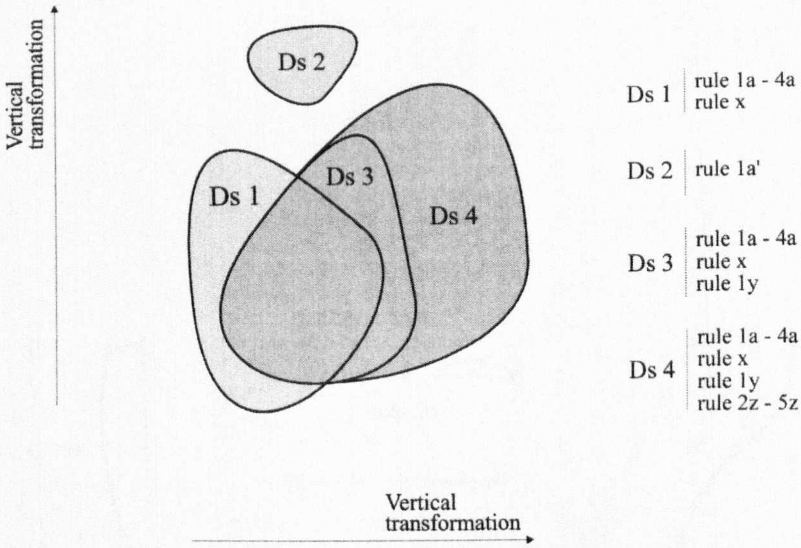


Figure 8.25. Ds 4 overlaps with Ds 1 and is an expanded design space from Ds 3

8.3.4 Reinterpretation

Vertical transformations of the initial concept design are crucial in design stages where designers want to explore while their essence of a concept is retained. However, changes to the interpretation of concept designs are necessary for design exploration. These changes assist designers in reframing their design space which can lead to new design concepts. For example, Figure 8.26 shows a new interpretation (diagram of elements) of the initial concept design. This represents a lateral transformation.

This new interpretation leads to a different decomposition of the initial concept design. As a consequence, different outlines are defined, though some of them are kept as the outline in rule 4b. In this new decomposition rule 1b is composed of three connected arcs instead of one single arc, and rule 3b is composed of one single arc instead of three connected arcs. Similar to the first decomposition, rule 4b contains a mobile decomposition point which indicates that one extremity of the outline is connected to another one. In the new interpretation rule 4a relies upon rule 1b.

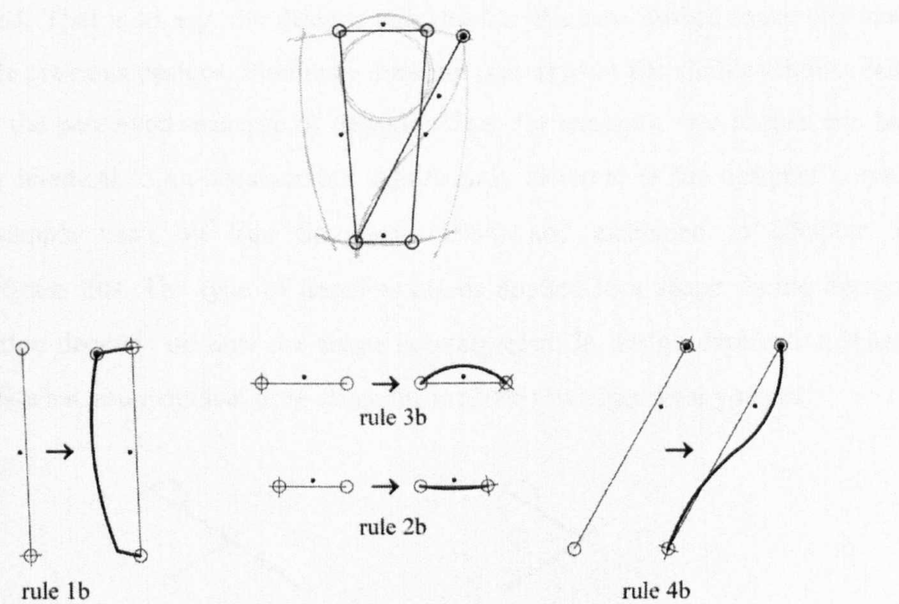


Figure 8.26. New diagram of elements and decomposition rules define a new interpretation of the initial concept design

Because rule 1b is applied in two instances the mobile decomposition point has two different positions which generate different sets of designs. Figure 8.27 shows a design family generated by the rules 1b - 4b and also by some rules defined earlier such as rule x and rule 1y.

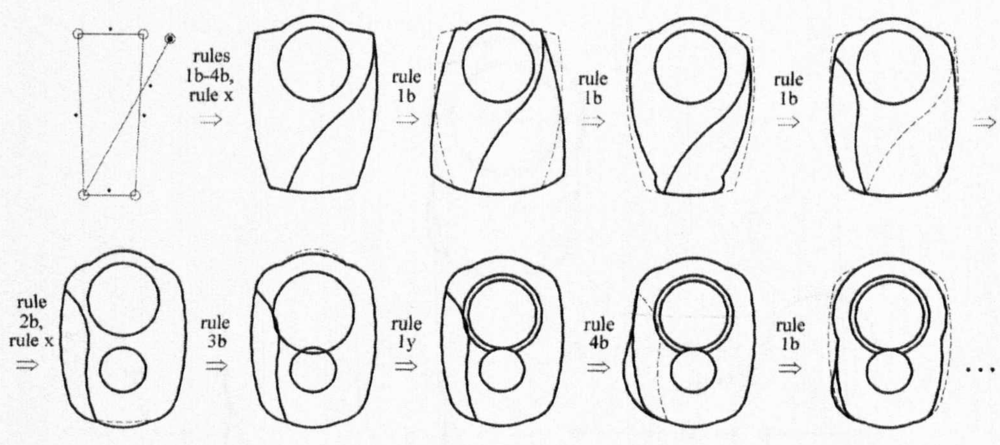


Figure 8.27. Design family that belongs to Ds 1_1

The designs illustrated in Figure 8.27 form part of a design space that cannot overlap with any of the previous design spaces – Ds1, Ds 2, and Ds 3 – even if it is expanded. That is to say, the designs contained in the new design space will not resemble previous designs. Similarity does not only rely on the visible outlines but also on the perceived structure of designs. Thus, for example, two shapes can be visually identical to an observer but significantly different in the designer's eye. The example used by Van Sommers (1984) and examined in Chapter 3 demonstrates this. The type of transformations applied to a shape during design exploration depends on how the shape is interpreted. In design exploration what counts is what you perceive, or to quote Stiny (2006) 'you get what you see'.

Figure 8.28. Similar shapes may belong to different design spaces (Van Sommers 1984)

The new design space (Ds 1_1) can be expanded, contracted, and displaced. All these design spaces will contain designs composed of the same elements. A reinterpretation of any of these designs will produce a lateral transformation which will define a new design space. Figure 8.29 shows a design chosen from Ds 1_1 (not illustrated in Figure 8.27) and five rules which reinterpret and decompose it.

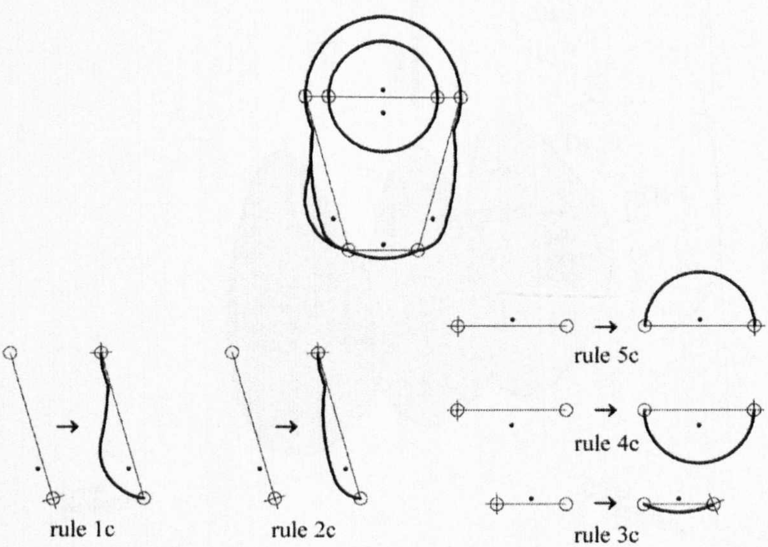


Figure 8.29. New diagram of elements and decomposition rules define a new interpretation of a chosen design from Ds 1_1

This new decomposition contains 5 rules in which the circle is not now defined via rule x but by decomposition rules. A corresponding design family is shown in Figure 8.30.

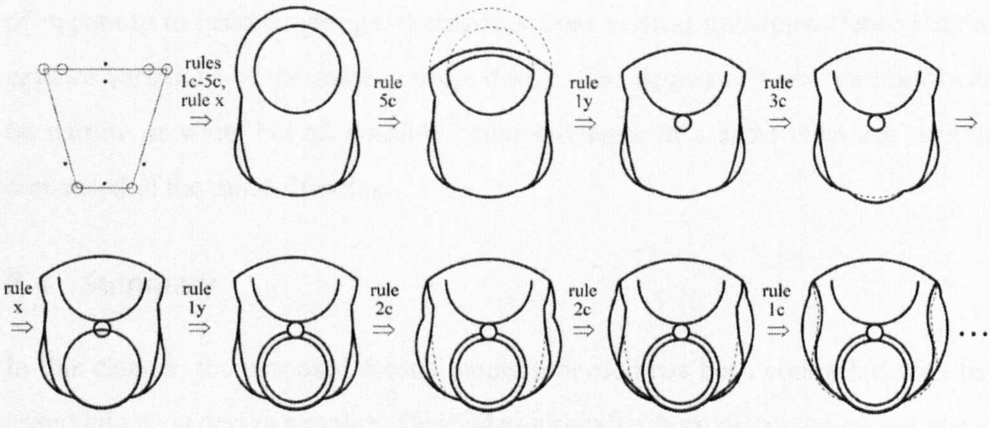


Figure 8.30. Design family that belongs to $Ds1_2$

In this family, by altering the values of the parameters in rule 5c the circle results in a lens shape, and therefore rule 1y can be applied. The new design space is labelled Ds 1_2. Figure 8.31 shows a schematic representation of previous design spaces – Ds 1, Ds 2, Ds 3, and Ds 4 – as well as the new ones – Ds 1_1 and Ds 1_2.

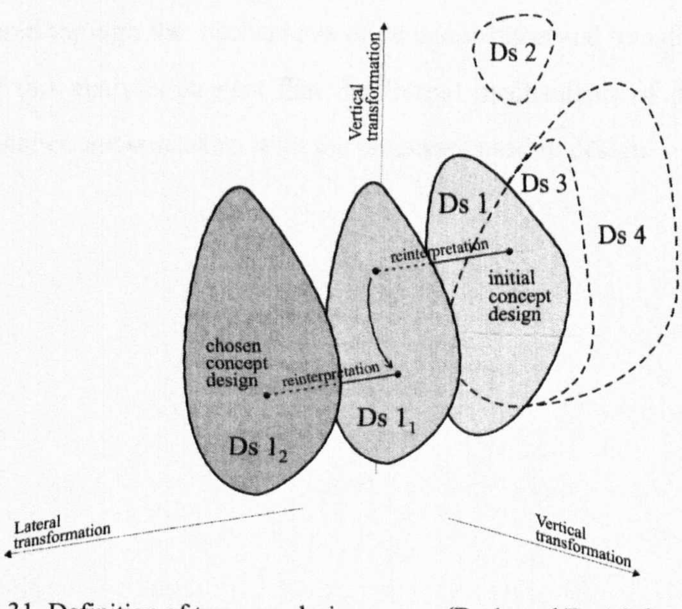


Figure 8.31. Definition of two new design spaces (Ds 1_1 and Ds 1_2) from lateral transformations

These design spaces are presented in a 3D view in order to differentiate between vertical and lateral transformations. While vertical transformations occur in the same level, lateral transformations result in a change of level. Once a lateral transformation has been realized a new design space is defined which offers a point of departure to generate design alternatives from vertical transformations. That is, explore variations of the same concept design. The degree of these variations can be narrow or wide, but all possible concept designs in a same level are seen as composed of the same elements.

8.4 Summary

In this chapter, the proposed formal model proposed has been contrasted with the observations on design practice. Their relationship has been discussed in two stages. First, the mechanisms used in the model – decomposition and transformation – have been examined in terms of the three processes used in design – reinterpretation, emergence, and abstraction. In addition, the generative mechanisms have been applied to show how the model can systematically duplicate a sequence of sketches generated by a participant. Second, the formal model has been applied in order to show how personal perceptions and intentions can be explored through the mechanisms of decomposition and transformation. The outcomes of this analysis suggest that the formal mechanisms of decomposition and transformation are consistent with the processes used in design.

Chapter 9

Conclusions and further work

9.1 Conclusions

The central objective of this thesis has been to show that generative methods acting on pictorial representations provide a feasible and valuable way to generate and explore product designs. This thesis has been presented in two connected parts. Part One examined the processes involved in shape exploration within design practice. It was argued that sequences of exploratory sketches trace systematic and logical paths from ideas to designs. This argument led to the examination of formal systems in design and their scope to model the development and transformation of pictorial representations, particularly sketches. Part Two presented a model that generates sequences of pictorial representations via formal mechanisms of decomposition and transformation of shapes. The last chapter has shown that these mechanisms are consistent with three types of activity; reinterpretation, emergence, and abstraction, which designers use when developing designs through pictorial representations. Further the chapter has suggested ways in which computational tools might support exploration of early conceptual designs through their pictorial representations.

Product design is partly an exploration of shape. In fact, shape is one of the key determinants of a product's success and explorations of possible product shapes can improve chances of success. The process of shape generation and exploration in product design has traditionally been a human iterative process that involves, among other things, making freehand sketches. Computer based tools offer the possibility of supporting, and perhaps even partly automating, this creative design process. Of particular interest to the design community has been computer support for the processes of developing design ideas. Much of design thinking underlying these processes of developing design ideas is concerned with transforming concepts from one form to another.

One of the chief advantages of freehand sketches is that they have proved compatible with cognitive strategies for this transformational thinking. Understanding the significance of sketching in developing design ideas and exploring new ones has been the target of extensive research. The work reported here concentrates on three aspects. First, what kinds of changes or transformations are made to sketches during concept design development. Second, how can these transformations be explained in terms of three processes – reinterpretation, emergence and abstraction. Third, to what extent can the transformations and resulting sequences of pictorial representations during development of a product design be modelled by using mechanisms of decomposition and transformation. These mechanisms have been expressed formally as shape rules. Each of these aspects informs how computer systems can support design exploration. The formal expression of decomposition and transformation mechanisms as shape rules is particularly relevant for potential possible computational implementation as a design tool. There is no reason to suppose that computer systems for supporting design transformation will rely on the sort of freehand sketching that is produced by human designers. However, pictorial representations in general will form a significant part of such computational support.

Although there are many processes that underpin transformations which occur during design exploration, this research has focused on three, namely reinterpretation, emergence, and abstraction. Each of these plays a critical role in developing pictorial representations and each appears to be essential in the development of creative designs. The sequences of pictorial representations of designs generated via the formal model of decomposition and transformations suggest that these processes, especially reinterpretation, may encourage designers to break out of initial design requirements and look at concept designs in a different way. It should be emphasised however that this research did not attempt to investigate the designers' mental processes directly but rather the manifestation of these processes in the development of pictorial representations produced by designers. In other words, this research was not about 'seeing', but about kinds of 'moving' or transformations in the conceptual stages of design.

The empirical study presented in this thesis showed that a simple examination of sequences of freehand design sketches reveals several aspects of 'moving' which are related to the three examined processes of design thinking. For example, it was observed that in some cases the participants used different strokes to generate two sketches that are apparently similar. This sequences of moves to generate one sketch use different elements from those used in the other sketch. There is a reinterpretation.

The present study, in its own right, produced some understanding of the processes of the development of product design sketches. However, it stands as a preliminary attempt to identify relationships between sketches. Further studies using other techniques are needed. Video recording, for example, might track stroke production in a more accurate way. This might assist the identification of instances of emergence and reinterpretation that are not apparent from a simple examination of completed sketches. It is acknowledged, however, that the sequences of sketches produced by designers in a lab could be significantly different to those produced in design studios. For example, the sketches in the latter may be more ambiguous and explorative than in the former.

Examples in the literature illustrate how the processes of reinterpretation and emergence work in simple and 'abstract' shapes. Less attention has been given to how these processes actually work in representations of products' shape. The empirical study in Chapter 3 provided a number of examples which show that, in product design, emergent shapes are more likely to be discovered through transformational processes than interpretative processes. However, the shape grammar literature largely deals with emergent shapes associated with interpretative processes. In addition, the generative rules used in most implementations are applied to geometrical shapes composed of straight lines while product design involves shapes composed of curved lines. This suggests that the use of more elaborate shape descriptions is necessary for design generation.

The model for exploration proposed in this thesis is based on the key mechanisms of decomposition and transformation. The first allows pictorial representations of shapes to be decomposed in a systematic way at any stage within the generation process. The relationships between decomposition rules and the cognitive processes through which pictorial representations are perceived suggest that it is possible to generate sequences of designs through decomposition rules which correspond to changing perceptions of a shape. However, designs are not only developed according to how pictorial representations are perceived. The intentional and directed aspects of design processes prompt changes to these representations. Transformation rules allow the generation of sequences of design changes according to design intentions.

Decomposition rules are expressed in terms of a definition of a structural diagram of elements. Rules apply to elements in the diagram which transform shapes based on their structures. In the examples used in this thesis, the diagram of elements is composed of straight lines, but curved lines can also be considered. The diagram of elements is comparable to the organizational and abstract devices frequently used in design practice, such as axes, grids, and regulating lines. Similar to these devices, the diagram of elements establishes positions and relations between the elements perceived in a shape. Kolarevic (1997) demonstrated that such organizational devices used in architectural drawings become much more useful and interesting when they are used dynamically rather than as rigid structures. The research presented here shows that the consideration of dynamic diagrams of elements also enriches the exploration process in product design. On the one hand, dynamic diagrams expand the design space and therefore new types of vertical transformations can be explored. On the other hand, the definition of a different diagram for a particular shape – as a consequence of reinterpretation – assists in exploring the consequences of lateral transformations.

A drawback of designing with the proposed mechanisms of decomposition and transformation is that designers are forced to input formal descriptions, that is diagrams of elements and decomposition rules, that are not used explicitly in design practice. This demands an extra effort on a designer's part. It requires a deeper reflection on the pictorial representations that are used over and above intuitive operations on them. It is argued, however, that such effort may be countervailed by the fact that the model expands the designers' ability to explore the consequences of both their perceptions of the pictorial representations as well as their intentions. In principle the mechanisms in the model are potentially helpful to explore designs without being prescriptive. The mechanisms proposed are just that and they do not in themselves prescribe particular decompositions or directions of shape transformations.

Current 3D computer tools offer an indication of how designers accept more complex means of transforming shapes, if in turn, the outputs correspond to new ways of viewing a shape or allow designers to quickly explore new ideas and realise their design intention. The formal model offers the potential to capture not only those designs that were pictorially represented during the design process, but also to further explore designs that are consistent with the designer's perceptions and intentions. In particular the generation of families of related designs offers a powerful means of design exploration. To maintain these families within manageable sizes for designers to use, a mode of exploration using a hierarchy of families is described. Families can be explored by increasing or decreasing levels of detail corresponding to the definition of new design spaces that can be contracted, expanded, or displaced. At each particular stage, family members can be selected for further exploration. This mode of exploration might be particularly valuable for those designers who wish to make use of design precedents in their exploration. Expressing precedents in terms of a family of related designs provides a systematic and comprehensive exploration of the starting points in a design process.

Although the proposed model is still in the early stages of development, its effectiveness in decomposing and transforming shapes in a formal way suggests that a refined model could assist designers to creatively and systematically generate design families according to personal perceptions and intentions. This research indicates that designing with decomposition and transformation rules applied to pictorial representations provides a route to assist designers in expanding their capacity to creatively explore designs. Although this might not make the design process simpler and easier, it will expand a designers repertoire through allowing systematic presentation of related designs in families and their progressive refinement.

This research illustrates that although, in general, the shape transformations utilised in design sketches may be seen as simple and straightforward, formal representations of these transformations can be very complex. Such complexity is not only due to the variety of cognitive processes that are related to shape transformation in design, but also due to cognitive differences across design stages and design fields. In this thesis, in order to make this complexity manageable, the presented model was developed focusing on the initial stage of consumer product design. This means that, although it could be hypothesized that the mechanisms of decomposition and transformation also occur in other design stages and design fields, the conclusions drawn in this thesis refer only to this particular design stage and design field. In addition, the research has assumed that the only cognitive process related to shape transformations is visual perception. Other cognitive processes that might influence shape transformations, such as memory, mental imagery and expertise, were not considered. It remains for future research to examine the applicability of the presented model in other design stages and other design fields as well as to what extent the model supports other cognitive processes not considered in this research.

9.1.1 Contributions

The main contributions of this research are:

- Demonstration that sequences of freehand sketches support cognitive processes used in design exploration.

- Describing and analysing explicit examples of how the processes of reinterpretation, emergence, and abstraction are manifested in sketches produced by industrial designers.

- Developing a model of design exploration using mechanisms of decomposition and transformations expressed as shape rules.

- Application of the model to formally describe how pictorial representations develop as individual perceptions and intentions change during design.

- A method that allows explicit depiction of design families and definition of the design spaces to which these families belong. This method is applied to present a visual means to conduct exploration through generation of families and selection in a hierarchical process of progressive refinement.

- Demonstration of how the consequences of particular perceptions of pictorial representations and design intentions can be explored through applying the mechanisms of decomposition and transformation.

9.2 Further work

Several areas of further work are opened up by the work reported in this thesis. Here mechanisms for design exploration have been developed based on both empirical analysis of how pictorial representations are changed in product design, as well as theoretical analysis of the possible cognitive processes behind these changes. Further work includes:

1. More empirical studies are needed to confirm details of how changes are made. The empirical investigation reported here is indicative rather than conclusive as to what happens in pictorial representation as designs are developed. One avenue is to examine more closely the ways in which designers identify outlines, their constituent elements and associated structures. Further empirical work might ask designers to reflect on their sketches to identify the features of the outlines and identify structures on their sketches.

2. Formal descriptions of mechanisms for decomposition and transformation are the first step towards computer tools. How the model presented in this thesis could be computationally implemented remains as further work. Further work is needed to implement the kinds of shape rule on curved shapes that are required for product design. Approximation of free-form curves with piecewise line-rules could be further investigated especially in relation to the use of 'circular arcs' as features of composite curves

3. This thesis has presented a number of formal descriptions to be employed in design exploration. However, there are indeed many other different types of formalisms that can be used in design. This raises the following question: is it possible to choose one formal description over another? Can different descriptions follow the same exploratory paths?

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